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The 36th VLSI Forum: 0.3 Micron Lithography Technology

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NOTE TO READERS: Effective 1 October, the processing indicators appearing in brackets at the start of each item will be changed. All new indicators will begin with "FBIS" to make the material more easily identifiable. Some will also indicate whether the item has been translated from the vernacular or transcribed from English.

The 36th VLSI Forum: 0.3 Micron Lithography Technology

Attendees to the 36th VLSI Forum

94FE0815A Tokyo PRESS JOURNAL in Japanese 24 Jun 94 pp 6-7

[FBIS Translated Text]

Attendees to the 36th VLSI Forum

Name	Company
Ichiro Doi	Asahi Kasei Kogyo K.K.
Eiji Honda	Asahi Kasei Kogyo K.K.
Yasuo Tsukada	Asahi Kasei Denshi K.K.
Takaaki Kobayashi	Asahi Kasei Microsystems K.K.
Kazuhisa Onozawa	Asahi Denka Kogyo K.K.
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Toshio Mafune	Ishikawajima Harima Heavy Industries Co., Ltd.
Shinya Iida	Ushio Denki K.K.
Hiroyuki Kubo	Ushio Denki K.K.
Yukio Yasuda	Ushio Denki K.K.
Masaaki Niikawa	Ube Industries, Ltd.
Nobuaki Tsuji	NTT Electronics Technology K.K.
Ichio Hayashi	K.K. MBK Microtech
Hiro Mizogami	Oki Engineering K.K.
Fumitaka Yokoyama	Oki Electric Industries Co., Ltd.
Masaki Kakutani	Oki Electric Industries Co., Ltd.
Takahiro Yamauchi	Oki Electric Industries Co., Ltd.
Minoru Watanabe	Oki Electric Industries Co., Ltd.
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Yoshiki Takano	Canon Corporation
Takamasa Hirose	Canon Corporation
Makoto Kurotobi	Canon Sales Corporation
Masayuki Ando	Canon Sales Corporation
Makio Inui	Klien, Otto, Benson Shokengaisha
Shuichi Fukazawa	KTI Semiconductor K.K.
Korin Ike	Gendai Denshi Sangyo K.K.
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Yukihiro Takao	Sanyo Electric Corporation
Ryu Shimizu	Sanyo Electric Corporation
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Toshi Kumazaka	Shipley Far East K.K.
Katsunori Yoshinaga	Sharp Corporation
Shuji Tanaka	Sharp Corporation
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Foreword by Forum Chairman

94FE0815B Tokyo PRESS JOURNAL in Japanese 24 Jun 94 pp 9-11

[Article by Yasuo Suii, professor at Waseda University]

[FBIS Translated Text] Lithography is the fundamental technology for downscaling integrated circuit (IC) geometries, and research and development work in this area is being steadily pushed forward. At the cutting edge of photolithography, we are now reportedly capable of defining 0.15μm lines using an argon-fluoride (ArF) laser beam under laboratory conditions, and in the area of nonoptical imaging, various preparations are being made for the future in the fields of electron beam and X-ray exposure technologies for use in mass production operations.

For the purposes of this forum, we took a step back from these cutting-edge technologies, and focused instead on 0.3μm lithography techniques that will commence being used in the near future in large-scale mass production operations, studying the process and device technologies and providing fodder for the decision mills concerning the selection of i-line and excimer laser capabilities.

As I never fail to point out, the formulas for expressing resolution (R) and depth of focus (DOF) in photolithography are as follows:

$$(1)\ R = K_1 \lambda/NA \qquad (1)$$

$$(2)\ DOF = K_2 \lambda/(NA)^2 \qquad (2)$$

Here lambda (λ) represents the wavelength of the exposing energy, NA stands for the numerical aperture of the lens and K_1 and K_2 are constants representative of photoresist characteristics and exposure methods.

As is evident from these formulas, basically, reducing the size of the exposing energy wavelength (λ) is an effective means of achieving tinier feature sizes, and, as shown in Figure 1, there has been progress with step-and-repeat imaging techniques that employ high-pressure mercury arc lamps as the source of energy, these steppers having reduced wavelength from the g-line to the i-line level.

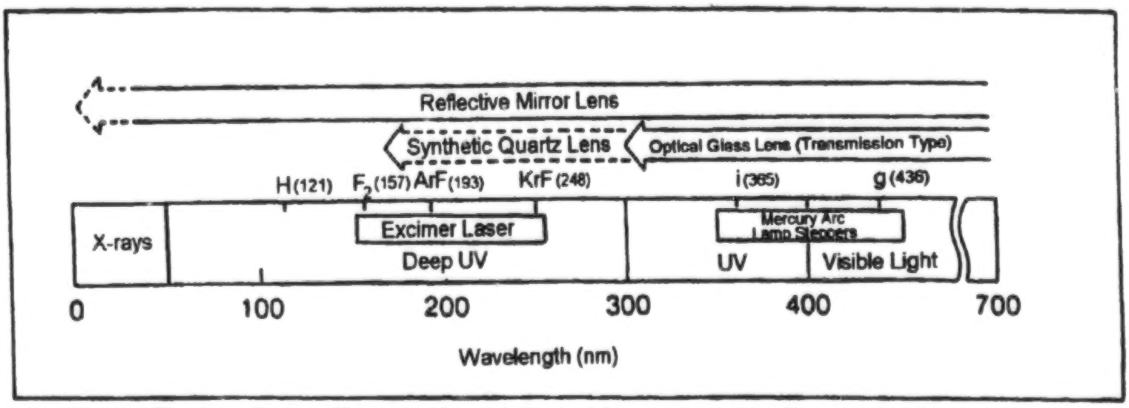

Figure 1. Energy Wavelengths and Optical Systems Used in Transfer Equipment

However, because it is impossible to obtain lens materials with multiple refractive indices, for all practical purposes, chromatic aberrations cannot be corrected below around 300nm. For wavelengths shorter than 300nm, there are two options available. One of these options is a method for narrowing the wavelength band of the energy being used until it approaches monochromatic light. Excimer laser lithography is such a method. This approach utilizes the already narrow bandwidth energy created by the excimer laser and further narrows the bandwidth of the laser energy to less than 3pm using etalon and other optical devices. As indicated in Figure 1, another approach currently being employed makes use of a reflective mirror lens (catadioptric technique), taking advantage of this lens's low wavelength dependency to reduce the size of the projection as much as possible.

However, as might be expected, huge, well-established industries like the IC industry tend to try to avoid as much as possible changing from technologies they are already accustomed to using in their plants. The industry is, therefore, making efforts to extend conventional mercury arc lamp i-line technology. These efforts are aimed at ultra-high resolution techniques such as phase shifting and off-axis illumination, approaches that attempt to make the constants (K_1 and K_2) in formulas (1) and (2) above smaller. These methods have also made it possible to achieve 0.3μm feature sizes.

Nevertheless, both the excimer laser and catadioptric methods have already reached the practical stages of their development, and it is believed that manufacturers will have to switch to these approaches once i-line technology finally reaches its limits. Just when, or at what stage this switch will be made will most likely be decided based on each company's judgment concerning its experience with, ideas on and current level of lithographic technology. This forum was put together to contribute toward those judgments.

Current State of i-Line Ultra-Resolution Techniques (Phase Shifting, Off-axis Illumination)

94FE0815C Tokyo PRESS JOURNAL in Japanese 24 Jun 94 pp 13-22

[Article by Junji Miyazaki of Mitsubishi Electric Corporation's ULSI Research and Development Laboratory]

[FBIS Translated Text]

Introduction

The ever higher integration of ultra large scale integration (ULSI) devices knows no bounds. Design rules of 0.25μm have been attained in the laboratory, and industry is seeking 0.3μm-microlithography processes for use in volume production operations. The downscaling of patterns to date has relied on enlarging the numerical aperture (NA) of the lens and shortening the wavelength of the exposing energy in accordance with the Rayleigh formula, i.e. $R = k_1 \lambda/NA$ (hereafter formula (1)). However, increasing NA, as indicated in the formula $DOF = k_2 \lambda/NA^2$ (hereafter formula (2)), causes problems from the standpoint of reduced depth of focus (DOF), but there are no prospects for enhancing the practical resolution that would enable the required DOF to be achieved. And when it comes to shortening wavelengths using deep ultraviolet (DUV) energy sources such as krypton-fluoride (KrF) excimer lasers, the considerable tasks of developing photoresist materials and process technologies remain, as do the need to lower the costs involved in this approach. Therefore, in order to define feature sizes shorter than the wavelength of light used to produce them using conventional i-line technology will require the use of so-called ultra-resolution techniques. This paper discusses recent trends in i-line ultra-resolution techniques.

Ultra-Resolution Techniques

Stepper imaging systems are generally described as follows. The light from a mercury arc lamp is passed through a fly's eye lens, forming a multiple point source of light, or secondary light source. The energy generated from this source irradiates the mask, giving rise to the diffractive light that emanates from the mask in accordance with the mask pattern. This diffracted light is aimed at a projection lens which projects these diffracted light beams onto the surface of the wafer, where they image the photoresist. Light with a large angle of diffraction cannot be used with a projection lens. Ultra-resolution techniques is the generic name for technologies that form filters that control the phase and transmittance in parts of imaging systems such as this. Ultra-resolution techniques are broadly divided into three types: the phase-shifting mask[1] that works on the mask plane, off-axis illumination methods[2] that work at the light source plane, and pupil filtering methods[3] that operate on the plane of the lens pupil (see Figure 1). We will discuss only two of these approaches here: phase-shifting and off-axis illumination.

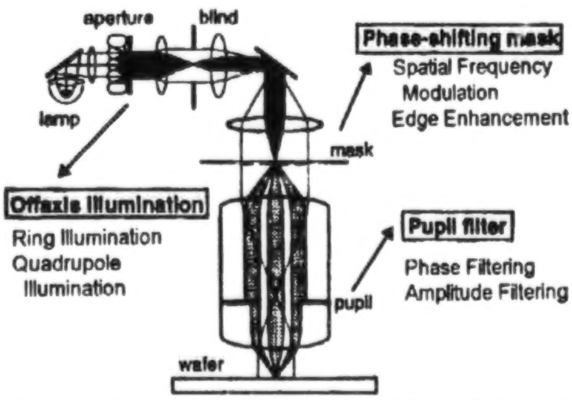

Figure 1. Stepper Imaging System and Ultra-Resolution Techniques

Phase-Shifting Methods

Phase-shifting methods can be broken down into spatial frequency modulation and edge enhancement types.

Representative of the spatial frequency modulation type are the Levenson type phase-shifting mask[1] and the transmission type phase-shifting mask.[4] These methods get their name from the fact that phase shifters formed every other repeat pattern serve to double the pattern cycle period. Spatial frequency modulation type phase-shifting methods can greatly improve resolution and DOF, but some of the drawbacks associated with these approaches are a limited number of applicable patterns, the need to employ negative photoresist processes and the difficulties encountered in trying to produce high-precision masks. Edge enhancement methods, on the other hand, are means of improving the edges of optical images, and include among others the auxiliary pattern,[5),6)] rim,[7),8)] and half-tone[9)] type phase-shifting masks. Although the degree of improvement capable with edge enhancement methods is small compared to spatial frequency modulation approaches, on the up side, these methods can be used with conventional positive resist processes and do not suffer from pattern layout restrictions. The half-tone (or attenuated) type phase-shifting mask in particular is developed using a single-layer film[10)] and can be manufactured using conventional means, factors which have focused attention on this approach as a practical phase-shifting method.

Levenson Type Phase-Shifting Method

By placing phase shifters at every other repeat pattern, the Levenson type phase-shifting mask can effectively double the pattern cycle period (see Figure 2). Thus, whereas conventional shading type masks generate diffracted light of the zero-order, plus or minus first-order, plus or minus second-order and so on, Levenson type phase-shifting masks generate diffracted light that lacks a zero-order, and the plus or minus first-order, plus or minus second order and subsequent portions of which possess diffraction angles of one-half. As a result, in principle, this approach achieves twice the resolution of conventional methods, and because of the dual-beam interference by the plus or minus first-order light, defocus wave front aberration can be eliminated and an extended DOF can be achieved. However, since repeat patterns form the basis of Levenson type phase-shifting masks, when it comes to imaging isolated patterns, especially isolated left-over patterns (when using negative photoresists), the spacing of the phase shifters widens, making it impossible to achieve the phase-shifting effect. Pattern designs will have to take this characteristic into account in order to apply Levenson type phase-shifting masks to actual patterns (see Figure 3).[11)] Computer-aided design (CAD) tools are also essential to position the shifters with consistency. And in the mask-making process, failure to control with extreme precision the transmittance and phase difference of the phase shifters, i.e. if the shifters are not formed accurately, will have an adverse impact on pattern dimensions. It is also imperative that a negative resist process be developed.

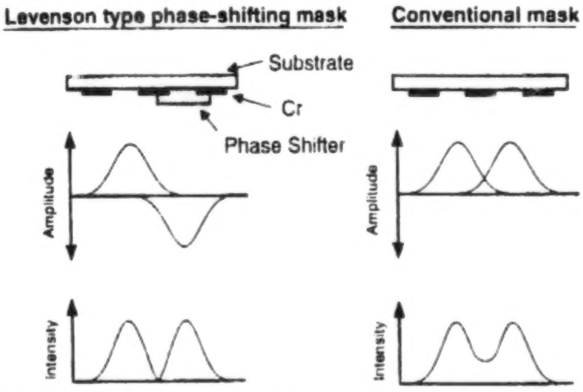

Figure 2. Principle of the Levenson Type Phase-Shifting Mask

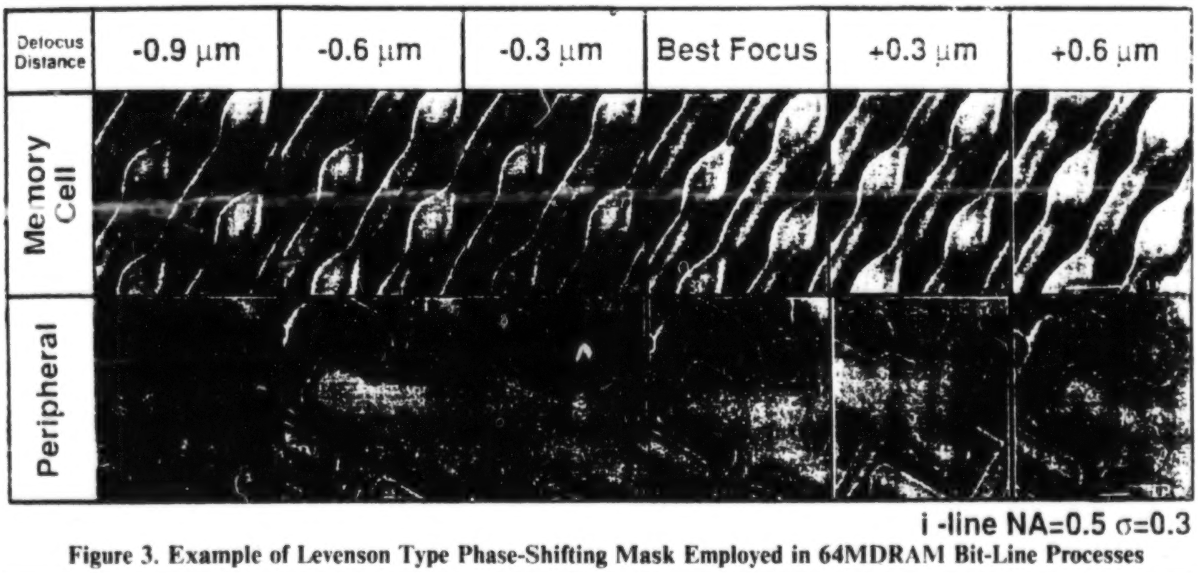

Figure 3. Example of Levenson Type Phase-Shifting Mask Employed in 64MDRAM Bit-Line Processes

Half-Tone Phase-Shifting Method

With conventional shading type masks, the optical image weakens and spreads out as a result of the diffraction of light during the pattern reduction process. Half-tone phase-shifting masks improve the optical image by enhancing transmittance by 5-20 percent in the conventionally shaded areas, and establishing a 180° phase difference at the openings. If we consider the optical image in terms of the amplitude of the light, the half shaded areas possess negative amplitude. Light intensity is the square of amplitude, and it (light intensity) always drops to zero once, making for a sharp optical image (See Figure 4). For example, when transferring a 0.35μm square hole pattern, whereas conventional shading type masks can only achieve a 0.6μm DOF, half-tone phase-shifting masks increase DOF to 1.5μm. Also, when a half-tone phase-shifting mask is used to transfer a pattern, film borders or fringes are generated in the vicinity of the holes as a result of side-lobe radiation. To keep these film borders from getting too large, mask transmittance and pattern oversize must be maximized.

Single-layer Half-tone Phase-shifting Mask

The phase shifters employed on half-tone phase-shifting masks used to be of two-layer construction, comprising a hyaline layer of spin-on-glass (SOG) to control the phase difference, and a thin chrome (Cr) layer to control transmittance. However, SOG is problematic in that it is an unstable photomask material prone to defects, and because of its very large refractive index, an approximately 4000 angstrom-thick layer is required on the phase shifter, which adversely impacts the three-dimensional or cubic effect of the etched portion of the shifter. But recent reports describe a method for simultaneously controlling both transmittance and phase difference using a single-layer film. As shown in Figure 6, it is possible to satisfy both transmittance and phase difference requirements at the same time using a film with

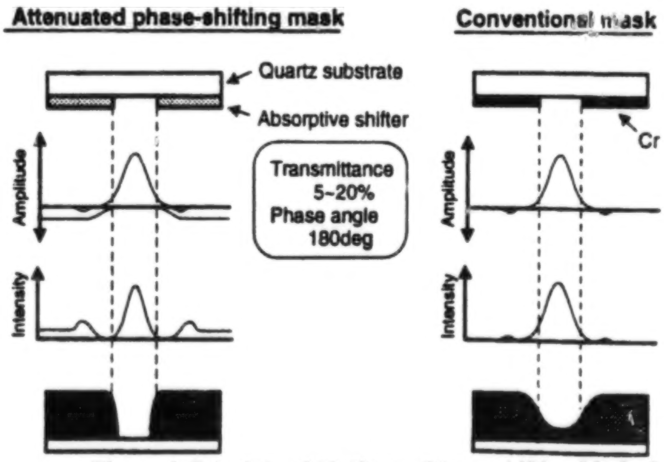

Figure 4. Principle of Half-tone Phase-shifting Method

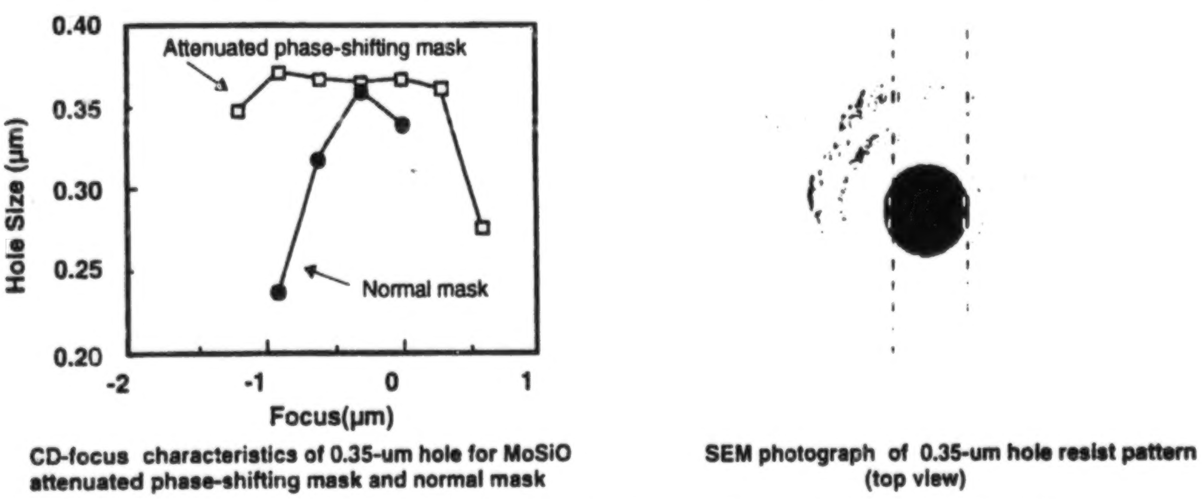

Figure 5. Characteristics of 0.35μm Holes Transferred Using Half-tone Phase-shifting Mask

a complex refractive index. This type of film can be formed from molybdenum-silicon-oxygen (MoSiO), molybdenum-silicon-oxygen-nitrogen (MoSiON), chromium-oxygen (CrO) or chromium-oxygen-nitrogen (CrON). As for controlling the complex refractive index, this can be accomplished, for instance, via the O_2 flow when argon (Ar) + O_2 is sputtered on a MoSi target (Figure 7).

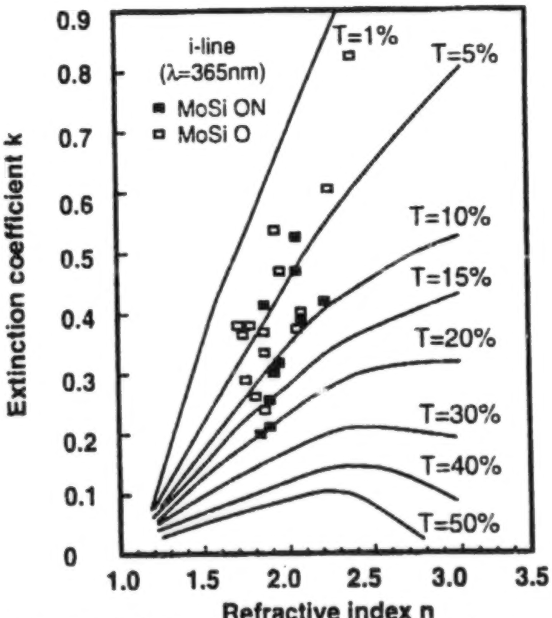

Figure 6. Relationship Between Complex Refractive Index and Transmittance With Half-tone Phase-shifting Mask

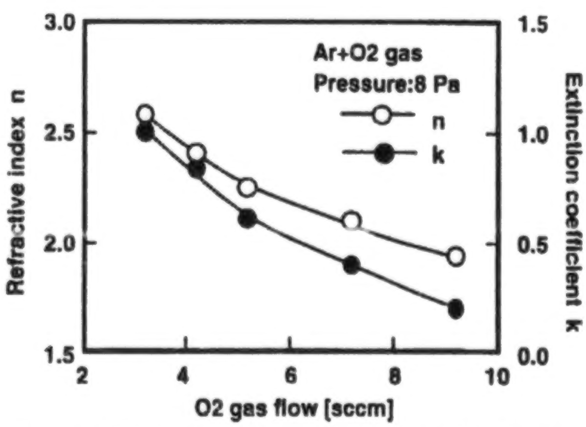

Figure 7. Control of Complex Refractive Index Via O_2 Gas Flow During MoSiO Sputtering

Single-layer half-tone phase-shifting masks have the advantage of being capable of being manufactured using conventional mask-making processes. A blank comprised of a glass substrate coated with a MoSiO film is topped with a Mo film that serves as the anti-static layer during electron-beam writing, and this in turn is coated with a layer of electron beam-sensitive resist. Following electron beam exposure and development, the MoSiO and Mo layers are dry etched using a CF_4 + O_2 reactive ion etch (RIE). Finally, the photoresist is removed via an O_2 plasma process and the Mo layer is removed using a wet etching process to complete the manufacture of the phase-shifting mask (Figure 8).

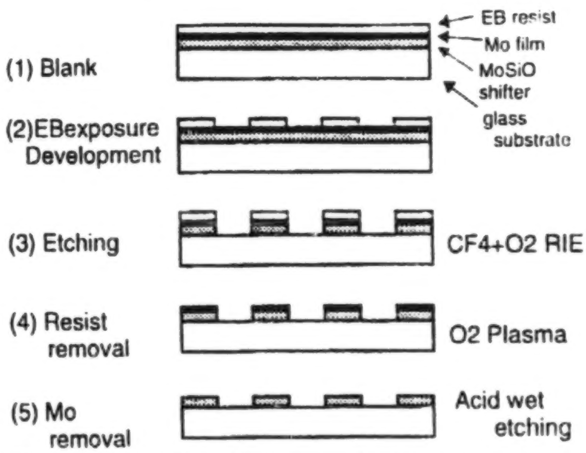

Figure 8. Manufacturing Process for Single-layer Half-tone Phase-shifting Mask

Conventional methods can also be applied to repairing defects in single-layer half-tone phase-shifting masks. Figure 9 shows a shifter residue defect (black-spot defect) repaired using laser ablation, and a pin-hole defect repaired via a focused ion beam carbon deposition process.

A problem peculiar to half-tone phase-shifting masks is multiple exposure at shot boundary lines during stepper exposure processes. As shown in Figure 10, conventional steppers have used shading layers for shot seams. This has resulted in film borders or fringes caused by multiple exposures with half-tone phase-shifting masks. A shading pattern must therefore be formed in order to lower transmittance in the vicinity of the exposure pattern created by half-tone phase-shifting mask. Making the dimensions of this shading pattern smaller than the stepper's resolution limits so that the surface ratio of the half shading layer and opening corresponds to transmittance enables the energy to negate itself, thus reducing transmittance.

Phase Angle Precision

A problem associated with phase-shifting masks that heretofore did not exist with conventional masks is the control of phase angle. A deviation or shift from the 180° phase angle of a half-tone phase-shifting mask equates to a shift from 180° in the phase difference of the radiation transmitted to both the opening and the half shading area. A phase difference occurs between the zero-order

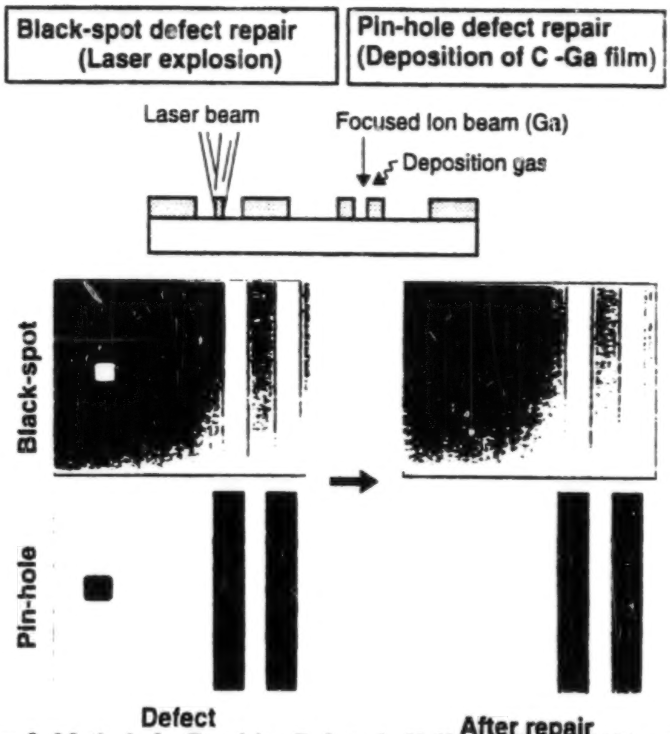

Figure 9. Methods for Repairing Defects in Half-tone Phase-shifting Masks

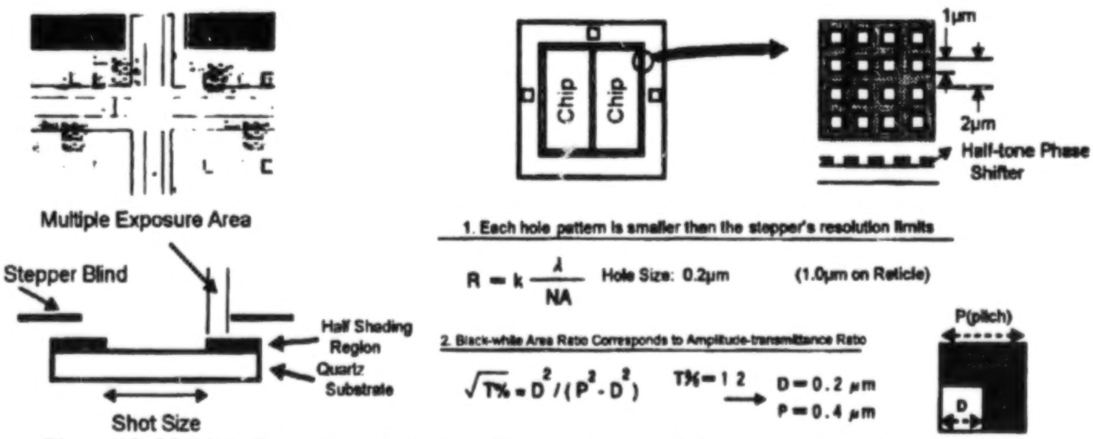

Figure 10. Multiple Exposure and Shading Countermeasures in Vicinity of Exposing Energy Shots

and higher-order diffracted light generated when this happens (Figure 11). A phase difference between diffracted bands of light is a phenomenon equivalent to wave front aberration, i.e. defocus. Therefore, a defocus equivalent to the phase shift will cancel out or offset the phase shift, resulting in a phenomenon corresponding to a shift in best focus at pattern transfer. This phase-shift-generated best focus shift reduces practical DOF, requiring that the precision of the phase angle be around 3° in order to keep best focus within 0.1μm of the reduced DOF brought on by the phase shift (by the reduced phase shift effect) (Figure 12).

Off-axis Illumination Methods

Using stepper optical system imaging techniques to illuminate the periodic pattern on a mask generates diffracted light in response to that period. This diffracted light passes through a projection lens and is converged on the wafer, where, via interference, it images the mask pattern. To form the image on the wafer, at least two bands of diffracted light must emanate from the projection lens. Ordinarily, therefore, stepper resolution is the pattern size that the plus or minus first-order light passing through the lens pupil can achieve.

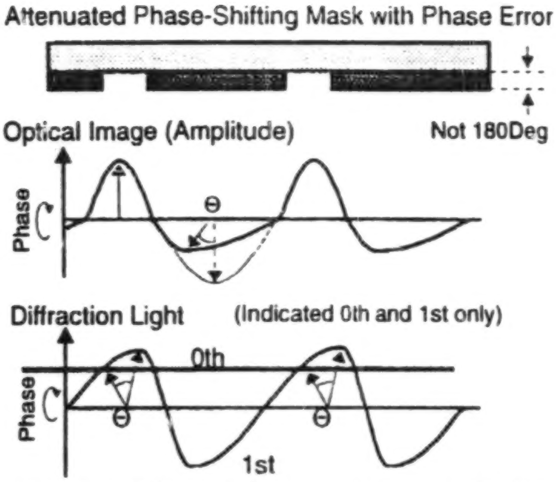

Figure 11. Effects of Phase Angle Error on Optical Image and Diffracted Light

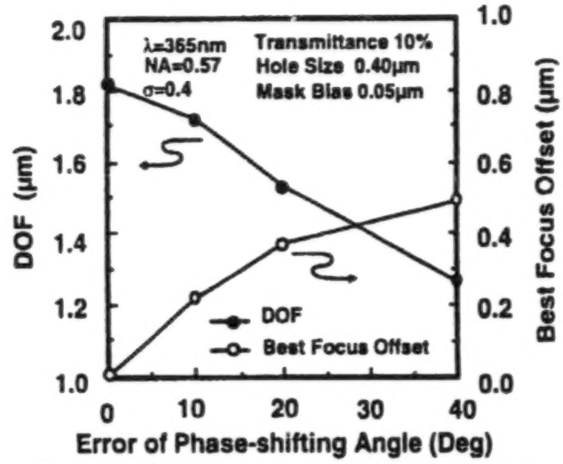

Figure 12. DOF Reduction and Best Focus Shift Resulting From Phase Angle Error

With off-axis illumination, since the mask is illuminated at an angle, imaging is achieved with only two beams, zero-order and + first-order bands of diffracted light. This makes possible resolution up to twice the periodic pattern capable with conventional imaging methods. Also, this dual-beam interference reduces the phase shift of the diffracted light bands at defocus, increasing the focal depth (Figures 13 and 14). Off-axis illumination methods include quadrupole illumination,[12),13)] which is effective for XY-direction patterns only, and circular illumination, which, although only marginally effective, is not limited direction-wise as to the patterns to which it can be effectively applied.

Pattern Dependency

Off-axis illumination is most effective when used to image specific periodic patterns. For example, off-axis illumination is extremely effective at imaging patterns such as those fabricated in storage node processes (Figure 15). By optimizing the shape of the illumination in a minute periodic pattern, off-axis illumination can achieve extremely large DOF. However, on the flip side, DOF decreases if the pattern deviates from the optimum pitch. In the case of a 1:1 line and space (L&S) pattern, off-axis illumination will improve DOF to 2.0μm in a 0.35μm L&S pattern, but if the pattern size increases, will only be capable of achieving a smaller DOF of

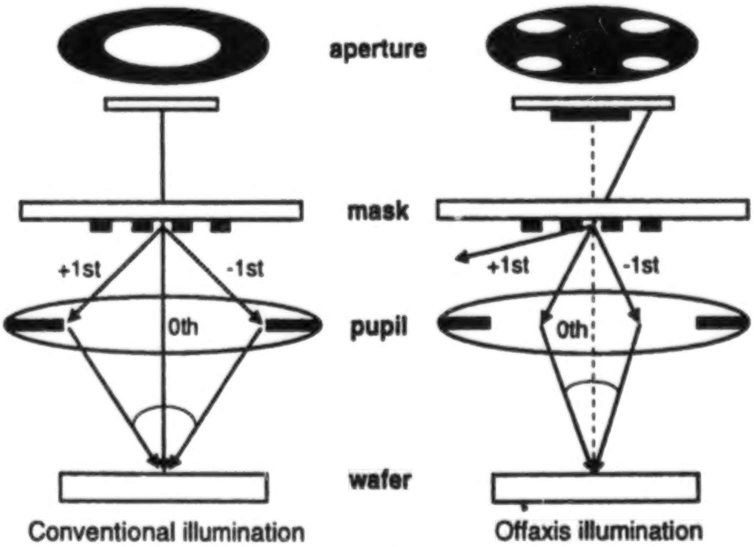

Figure 13. Principle of Off-axis Illumination Methods

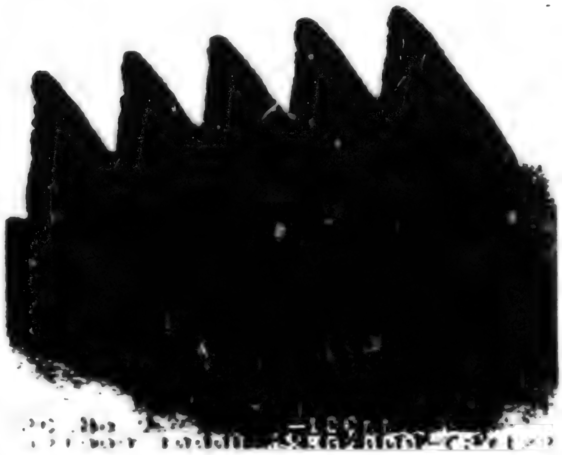

Figure 14. A 0.3μm Line & Space Pattern Formed Using Off-axis Illumination

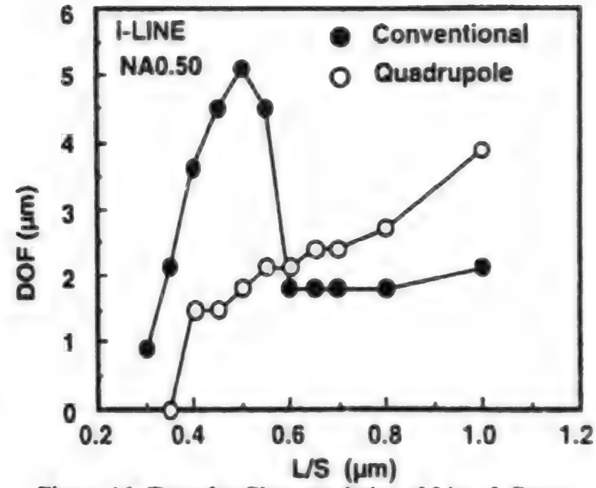

Figure 16. Transfer Characteristics of Line & Space Pattern Imaged Using Off-axis Illumination Method

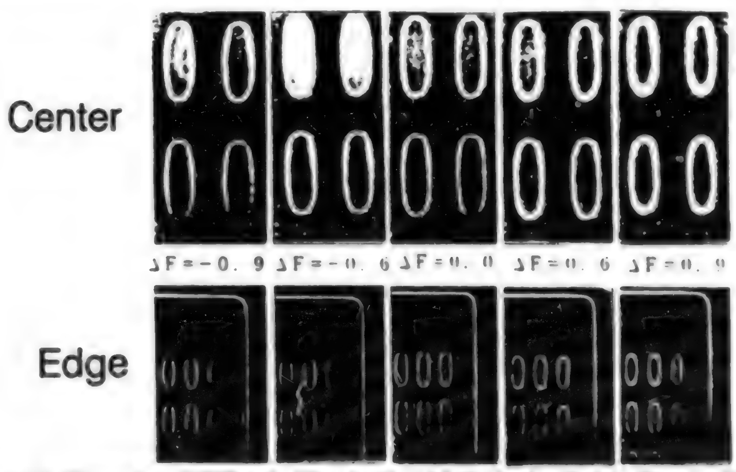

Figure 15. Examples of Off-axis Illumination Methods Applied to Storage Node Processes

around 1.8μm (Figure 16). This problem becomes increasingly serious if the duty ratio of a minute pattern deviates from 1:1. Figure 17 shows the effect on DOF of varying space width while maintaining line width at a fixed 0.35μm. DOF decreases when the pattern pitch deviates from the optimum value, and when space width reaches 0.6-0.8μm, there is hardly any DOF at all. In this regime, DOF decreases as a result of the resist dimensions becoming narrower than the design dimensions (Figure 18). This phenomenon is explained as follows. Second-order light elements gradually increase as the pattern period gets larger and the duty ratio deviates from 1:1 (Figure 19). However, these second-order light elements are practically all shaded by the off-axis illumination. This increases the relative intensity of the zero-order light, making the line thinner (Figure 20). Sizing and other such procedures must be employed to avoid problems brought on by the eclipse of second-order light in patterns for which the pattern pitch has deviated from 1:1 like this due to off-axis illumination. And combining an off-axis illumination technique with a half-tone phase-shifting mask effectively compensates the intensity balance of each order of diffracted light.[14] Measures will also have to be developed to deal with drops in illuminance and illuminance nonuniformity in steppers before off-axis illumination methods can be practicalized.

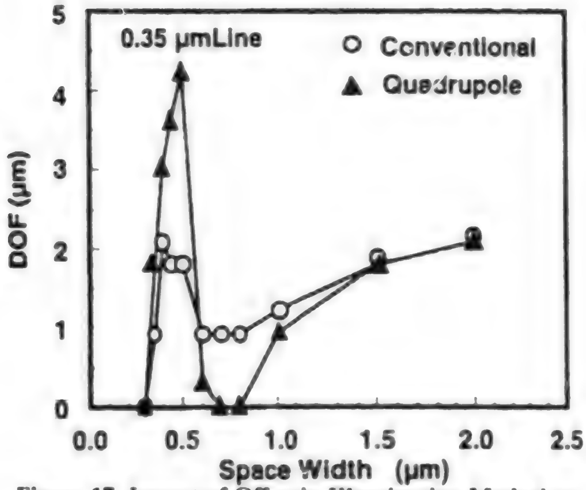

Figure 17. Impact of Off-axis Illumination Method on 0.35µm Line Pattern

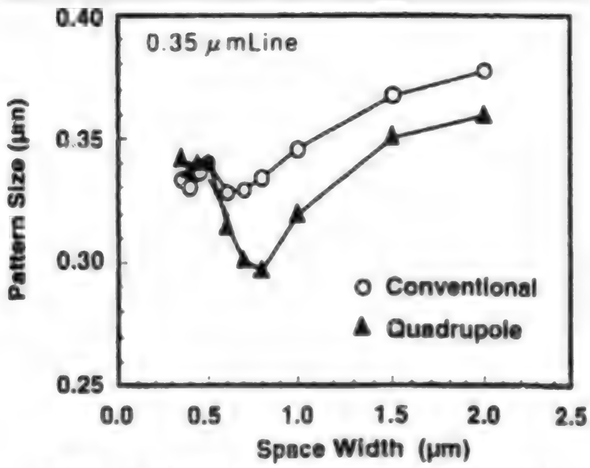

Figure 18. Critical Dimension (CD) Linearity of a 0.35µm Line Pattern

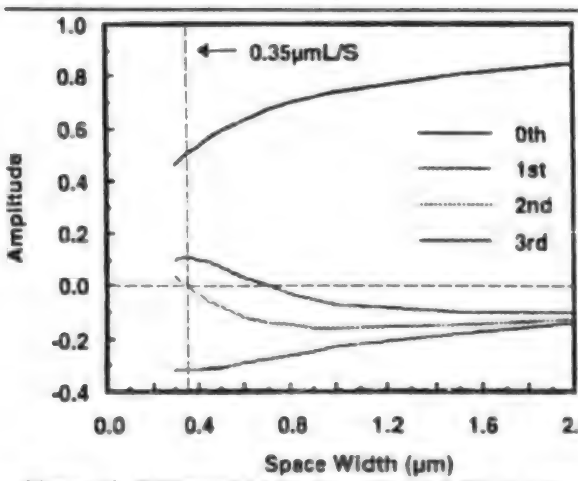

Figure 19. Diffracted Light Intensity of 0.35µm Line Pattern

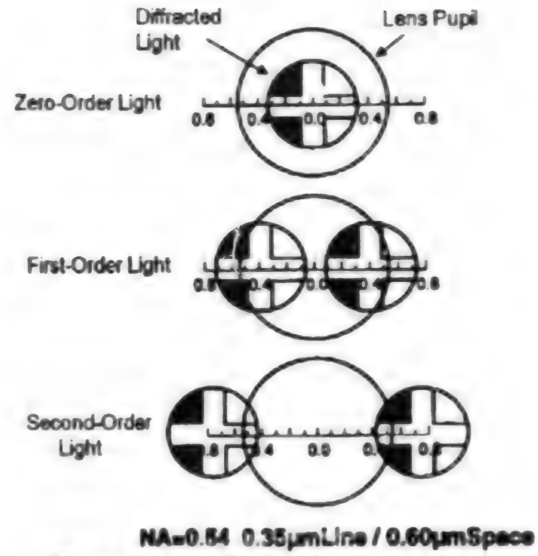

Figure 20. Lens Pupil and Diffracted Light

Conclusion

Development work is moving ahead on combining 0.3µm i-line lithography technology with ultra-resolution techniques such as those discussed herein, but a number of tasks remain before these combinations can be practicalized. And more than just ultra-resolution techniques will be needed to practicalize this technology at the 0.3µm level; progress in the fields of resist materials and processes will also be imperative.

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Maturity of Phase Shifting Masks

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[FBIS Translated Text]

1. Introduction

I will talk about the maturity of phase-shifting masks from the standpoint of a mask developer. Figure 1 shows the structure and principle of phase-shifting masks. I will focus my presentation on half-tone type phase-shifting masks, which we have recently developed and started manufacturing.

2. Phase-shifting Mask Maturity and Market Outlook

Half-tone (attenuated) phase shifting masks for use with i-line and g-line exposing energies are technologically mature enough for use in volume production operations and have recently begun to be marketed by mask manufacturers. Effective in the imaging of contact holes in 4- to 64-megabit dynamic random access memory (DRAM) devices, and with potential application in logic device imaging processes as well, the market for half-tone phase-shifting masks is expected to be large. Mass production of these masks should therefore prove successful.

Another type of phase-shifting mask that is practically mature is the shifter edge transfer mask. However, the market for these masks will be small as they are applied almost exclusively to the imaging of minute gates in high mobility transistors for use in satellite communications. The mass production of shifter edge transfer phase-shifting masks, therefore, would probably not prove very successful.

Spatial frequency modulation (Levenson type) phase-shifting masks are in the prototype stage of their development, and have not matured to the production technology level. However, they are effective in imaging routes and storage nodes for 64MDRAM, and could possibly find use in the fabrication of logic devices as well. There is, therefore, a potentially large market for these masks, and their mass production is expected to prove successful. Expectations run high for the future development of spatial frequency modulation phase-shifting masks.

Other types of phase-shifting masks (including auxiliary shifter, rim, shifter-shading and chromeless phase-shifting masks) are in the prototype stages of their development, and are still immature as far as production technologies go. Development will likely accelerate once one or more of these types of masks are judged by the market to possess inherent advantages.

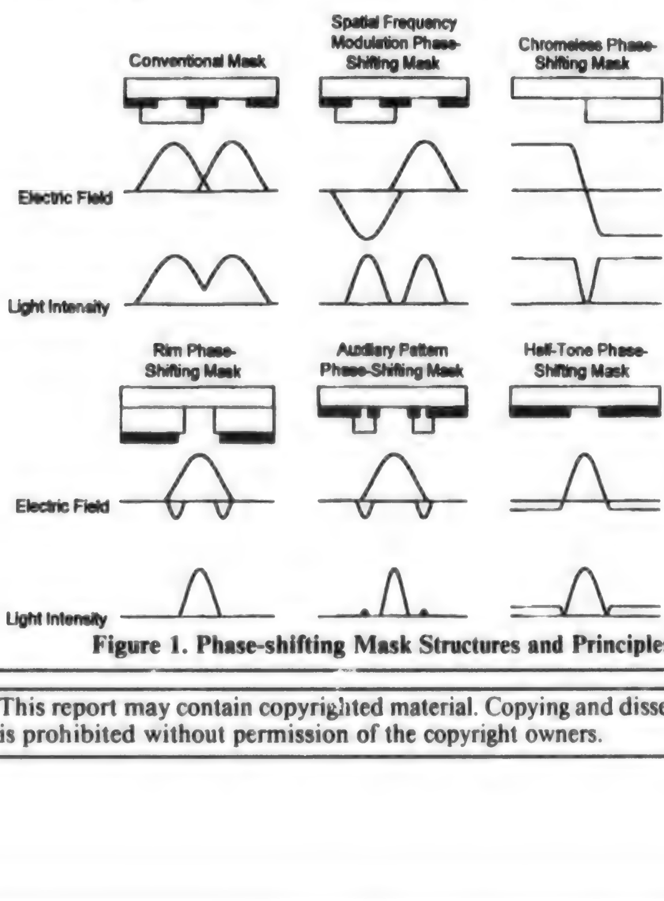


Figure 1. Phase-shifting Mask Structures and Principles

3. Maturity Levels for Respective Types of Masks

3.1 Shifter Edge Transfer Phase-shifting Mask

The shifter edge transfer phase-shifting mask is characterized by its use of the sharp collapse of light intensity that occurs as a result of phase inversion at the edge of the phase shifter, and its ability to form extremely thin isolated patterns by exposing negative photoresist possessing surface insoluble characteristics. Exposure dosage can be used to adjust the dimensions of this resist. The focal depth budget is extremely large. With an isolated pattern as a basis, lift-off processing can be used to form metal gates. These minute gates are then put to good use as high-mobility transistors (the high frequency characteristics of which are important) for use in satellite communications.

The following advantages facilitate the manufacture of these masks:

1) Lenient phase specifications (+/- 10° with wide lines, and +/- 5° with narrow lines);

2) Shifter pattern overlap with shading pattern need not be that precise;

3) Since only the edge of the shifter is utilized, the defect assurance area need only be a narrow region that includes the shifter edge, making it easy to realize quality masks.

Drawbacks include the addition of a shifter formation process to the conventional mask-making process. With such a small market, there isn't enough demand to warrant construction of a dedicated production line for shifter edge transfer phase-shifting masks, and we are waiting to see what developments on other phase-shifting masks produce.

To prevent the generation of unnecessary resolution from the shifter edge, the current practice is to expose the pattern a second time using an ordinary shading mask. Technological development on shifter edge transfer phase-shifting masks is thus concentrating on improving the performance of these masks to enable single-mask exposure operations. There have been reports of attempts to place thin shading lines under the shifter edge. Although this approach widens resist width, it also increases resolution stability. And to adjust resist width, shading lines smaller than resolution limits are being placed perpendicularly under the shifter edge to change the length of that edge.

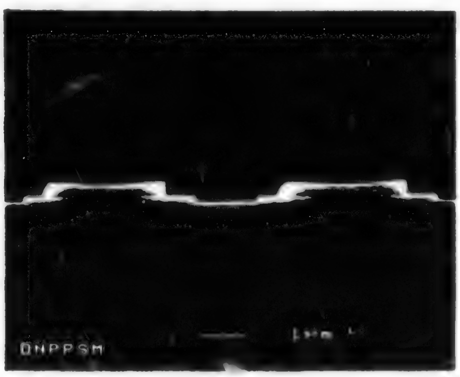
3.2 Spatial Frequency Modulation Phase-shifter Mask (Alternating Shifter and Levenson Types)

Alternately positioning normal patterns and shifter patterns makes the most effective use of the phase interference effect. There are two structures used to achieve this, an over-shifter structure and an under-shifter structure (see Photo 1), both of which have technical problems that need to be overcome. Numerous research reports have already been published, but due to the difficulty of manufacturing spatial frequency modulation phase-shifting masks, the development of off-axis illumination techniques for steppers and the enhanced performance of i-line resists, the need for and development trends related to these masks have dropped off temporarily. But with the practicalization of half-tone phase-shifting masks in sight, these masks are seen as prime candidates for development.

Recently, Hoga, et al.[1] have attracted attention by succeeding in producing a defect-free mask using orthodox methods aimed at facilitating production. The characteristics of their approach are as outlined below:

1) It was a negative mask. Therefore, multistage shifters were not required since there was no need to process shifter edges;

2) It was an over-shifter structure, meaning that a shifter layer could be formed and processed on top of a defect-free chrome (Cr) mask;



Over-Shifter Structure

Under-Shifter Structure

Photo 1. Spatial Frequency Modulation Phase-shifting Mask Structures

3) They used tried-and-proven spin-on-glass (SOG) as their material;

4) They applied wet etching to the SOG shifter, thus doing away with the need for the etch stop layer required for dry etching processes; and

5) They generated shifter layer data using dimension changes (only for those portions that correspond to zero-order energy) in the Cr layer data. This approach can be seen as simplifying the design method.

From the standpoint of safety, we were hesitant to introduce this approach into our manufacturing process where hydrofluoric acid is used in wet etching. On the premise of using a dry etch process, we therefore developed hafnium dioxide (HfO_2), with its high resistance to dry etching techniques, to use in place of the conventional etch stop material, tin oxide (SnO).

Some disadvantages peculiar to SOG are as follows: 1) It is very difficult to continuously manufacture in a stable fashion defect-free shifter layers using coating and baking processes; 2) Thickness variances have been observed when SOG is applied on top of a Cr pattern (Figure 2), and those tolerances can only be set using exposure evaluations. From the standpoint of quality assurance, it is therefore next to impossible to set up the specifications received from each user. And one drawback that SOG has in common with other materials is the difficulty encountered in trying to repair shifter defects, especially when those defects involve missing parts.

We are looking at SOG as a first generation material, and are pushing forward with development work on other materials and related processing methods. The two leading candidates for forming SiO_2 layers are a sputtering method and a chemical vapor deposition (CVD) method. With these methods, however, because irregularities occur in the shifter layer as well when a film is formed on top of the Cr pattern, we have no choice but to switch from an over-shifter to an under-shifter structure. There have been reports, however, that because the shifter in under-shifter structures is thick (380nm with i-line technology), the vertical side of the shifter adversely affects exposure energy scattering. To avoid this, attempts have been made to move the underside shifter edge back from the edge of the Cr pattern. However, it is doubtful this approach will become widespread due to the complex structure and processes involved.

3.3 Half-tone (Attenuated) Phase-shifting Mask

Half-tone phase-shifting masks are comprised solely of a semi-transparent shifter layer. The light transmitted through the main pattern interferes with the weak phase-inverted light transmitted via the shifter, making the intensity of the light passing through the main pattern slope steeply. This makes half-tone masks less effective than other types of phase-shifting masks (such as spatial frequency modulation masks). But these half-tone masks are good for imaging contact holes and isolated lines. Because there is strong demand from customers for lithography techniques designed to form micron-sized contact holes, even though not as effective at forming such holes as other types of phase-shifting masks (auxiliary shifter and rim type masks), half-tone phase-shifting masks were practicalized earlier than the other types because they are so easy to make.

Half-tone masks offer the following advantages: 1) They do not require special pattern designs (simply adding a positive bias to the hole dimensions will suffice); 2) They are single layer in construction; 3) Patterns are processed in a single run (writing, developing and etching); 4) Practically the same materials used to fabricate ordinary

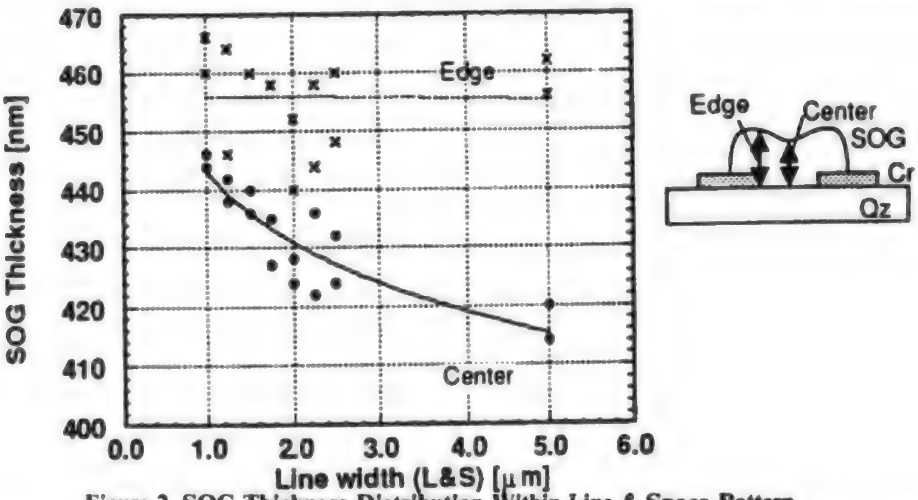


Figure 2. SOG Thickness Distribution Within Line & Space Pattern

masks can be used to make the phase shifters; 5) They can be manufactured on the same lines that produce ordinary masks, but dedicated defect inspection apparatus and quality (phase difference and transmittance) assurance techniques are required; and 6) They are potentially capable of approximating ordinary masks in terms of throughput and yield, delivery times and costs. And the development of a method for forming reticle frames (shading regions)[3,4] has eliminated one obstacle to practicalizing these masks.

I would now like to talk a little bit about the blanks[5] and mask processes,[6] defect inspection,[7] defect repair[7] and quality assurance[7] techniques related to the half-tone phase-shifting masks for i-line energy that we have developed. We have also developed half-tone masks for use with g-line energy, and are in the process of developing these masks for use with deep ultra-violet energy technologies.

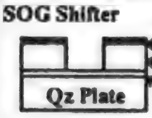
Blanks

After manufacturing and evaluating the four types of half-tone shifter structures and materials shown in Table 1, we came to the conclusion that the single-layer half-tone shifter was better overall. The materials reportedly used to date to fabricate single-layer half-tone phase shifters have been chromium oxide nitrides (CrO,[8-10] CrON[8-10]) with metal silicides (MoSiO,[4,9] MoSiON,[4,9] WSi[11]) and silicon compounds (SiN, a-Si:H).

We felt that a material comprised primarily of the chrome used in ordinary mask making would be preferable from the standpoint of manufacturing, and, independently of the above-cited reports, we came up with the following structures and shifter materials. That is, we developed bi- and tri-layer structures comprised of shifter and half-tone layers (hereafter referred to as the shading layer) like those shown in Figure 3, and of these, settled on the shifter layer/shading layer structure (Figure 3a). Figure 4 shows the spectral transmission factor of the i-line blanks and the optical constants (refractive index n and extinction coefficient k) of each layer thickness. This shading layer comprises a thin (10-20nm) film of CrN (material used in the manufacture of ordinary masks), and, at this thickness, controls transmission, while simultaneously possessing conductivity, a factor that enables it to act as an anti-static layer during electron beam direct write processes. The shifter layer makes use of CrON, a material with very high transmittance, and overall phase difference is controlled by the thickness of this layer. This two-layer structure is similar to the two-layer structure shown in Table 1, with the exception that the SOG has been replaced by a chrome oxide nitride.

The reason we opted for the multi-layer structure over the single-layer one is because it is impossible to achieve the numerous functions satisfied by the phase shifter layer with a single-layer structure. These functions are 1) Maintain phase difference at 180°; 2) Ensure i-line transmittance of between 4-10 percent; 3) Possess conductivity; 4) Maintain visible region transmittance at under 30 percent (with e-line and argon laser wavelengths); and 5) Maintain front and back surface i-line reflectance at suitable levels. Function 4 is necessary in order to use the current defect inspection device (KLA239HRL-PS) and microdimension measurement device (Nikon's MPA-3). We had difficulty satisfying functions 3 and 4 with our chrome-based single-layer

Table 1. Various Structures and Characteristics for Half-tone Phase-shifting Masks

Structures	Blank	Process	Inspection / Repair	Mask Cleaning	Total
SOG Shifter  Half-tone Chrome SOG Shifter Etch Stop Qz Plate	△	△	△~×	△~×	×
 SOG Shifter Half-tone Chrome Qz Plate	Defect-Free Fabrication	SOG Dry-Etching	SOG Defects Identification & Repair	Adhesion	
Qz Shifter  Half-tone Chrome Qz Plate	◎	△ Qz Dry-Etching	△~× Qz Defects Identification & Repair	○	△~×
Chrome Shifter  Chrome based embedded Half-tone Shifter Qz Plate	○	○	○	○	○

Evaluation Mark; ×: Poor, △: Acceptable, ○: Good, ◎: Excellent

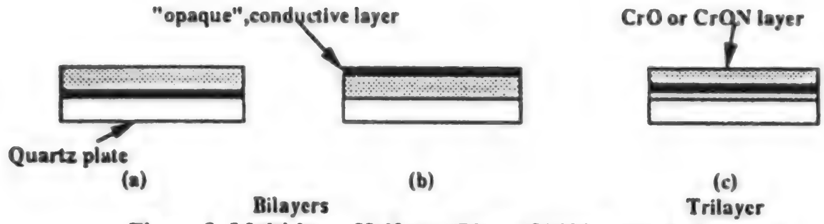


Figure 3. Multi-layer Half-tone Phase-Shifting Mask Structures

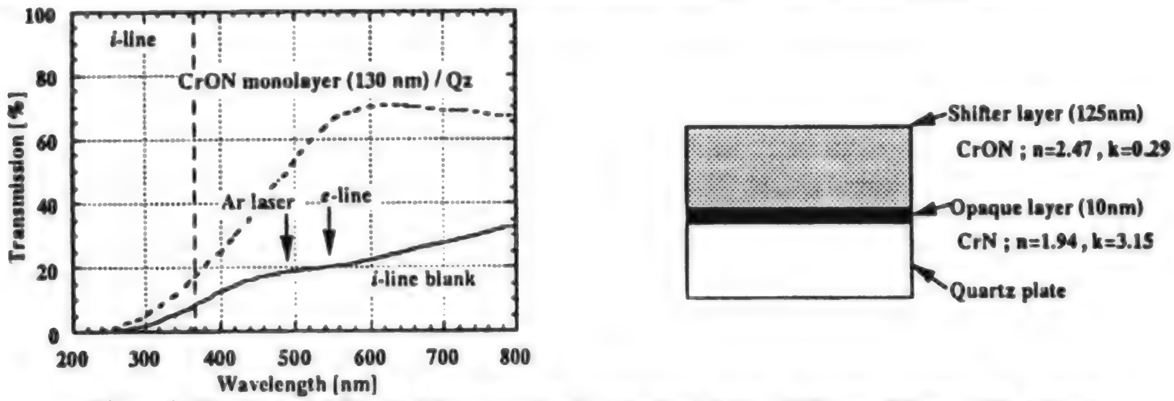


Figure 4. Structure and Spectral Transmission Factor of an i-Line Half-tone Phase-shifting Mask

structure, but by utilizing the two-layer structure, we have been able to satisfy these functional requirements.

We have also achieved g-line phase shifters by adjusting the thickness of the same construction shifter/shading layers found in the i-line half-tone phase-shifting mask. However, we are in the process of improving this structure for use with deep ultraviolet energy since the transmittance of the materials used in the shifter layer is too low.

When it comes to the characteristics required of a mask, we have confirmed that half-tone phase-shifting masks pose no practical problems since they 1) Possess radiation resistance of at least up to 1MJ/cm^2 (Figure 5); 2) Can withstand immersion (for one hour at 100°C) in concentrated sulfuric acid (Figure 6); and 3) Can withstand a weak alkaline solution.

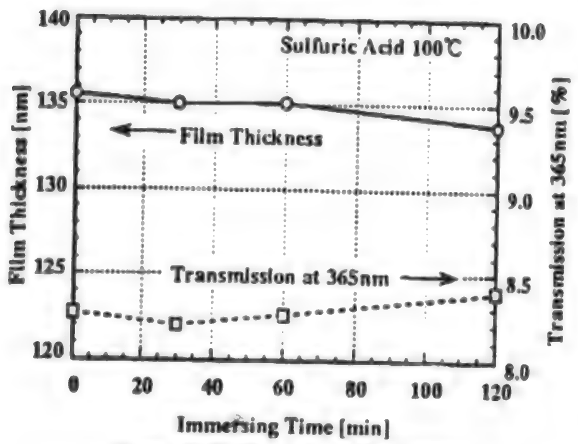


Figure 5. Sulfuric Acid Resistance

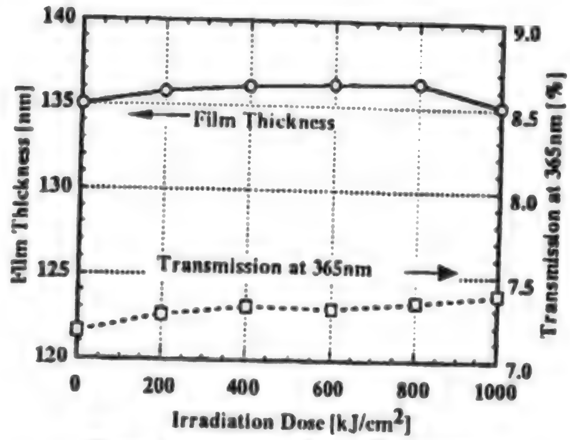


Figure 6. i-Line Irradiation Resistance

Masking Process

Table 2 shows the transition of specifications for ordinary masks (5x reticles) used in the imaging of successively denser DRAM devices. When using half-tone phase-shifting masks, in addition to these specifications, there are also specifications for phase difference and transmittance. For instance, the specification for phase

difference is 180° +/- 10° (target value: 180 +/- 5°), and that for transmittance is +/- 1 percent of the set-up value for the entire mask.

Table 2.

Item/Bit	4M	16M	64M
Minimum Feature Size on 5x Reticle	4.0	2.5	1.75
Critical Dimension	+/- 0.15 - +/- 0.10	+/- 0.10 - +/- 0.07	+/- 0.07 - +/ -0.05
Registration	+/- 0.15 - +/- 0.12	+/- 0.12 - +/- 0.10	+/- 0.10 - +/- 0.07
Defect Size	<1.0	<0.7	<0.5
Units: µm			

Initially, we developed a laser process, and now we are in the process of developing an electron beam process. In the laser process, we use a laser writing apparatus called the CORE-2564PS (manufactured by Etec Systems) to write the patterns in i-line resist, and then dry etch the half-tone phase-shifting mask using CH_2Cl_2/O_2. The cross section of the resist pattern is practically vertical, and the cross section of the shifter is also practically vertical. Photo 2 presents a cross section of a hole pattern. When it comes to the electron beam process, we were having problems selecting and utilizing resists with dry etch resistance, but this problem has now been solved. We are using MEBES-III and MEBES-IV (Etec Systems) and JBX-7000MV (JEOL). The critical dimensions distribution (2µm-wide pattern) shown in Figure 7, and the example of positioning accuracy provided in Figure 8 indicate our optical process capabilities. These bar graph data are the results of tabulations done on seven substrates, each six inches square and 0.25-inches thick. The results were satisfactory.

Photo 2. Cross Section of Half-tone Phase-shifting Mask

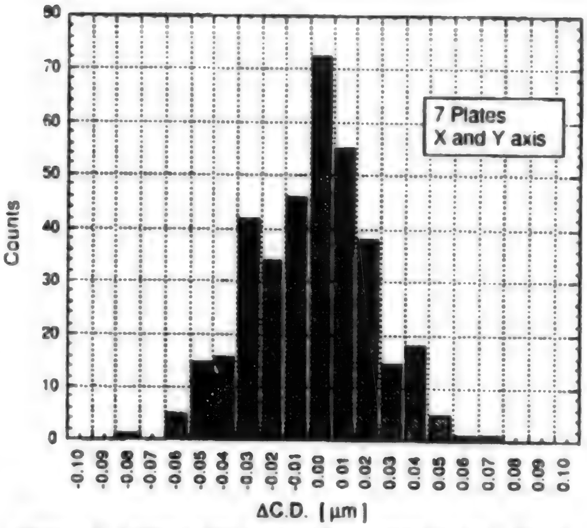


Figure 7. Critical Dimension Data Obtained on Seven Substrates Measuring Six-inches Square and 0.25-inches Thick

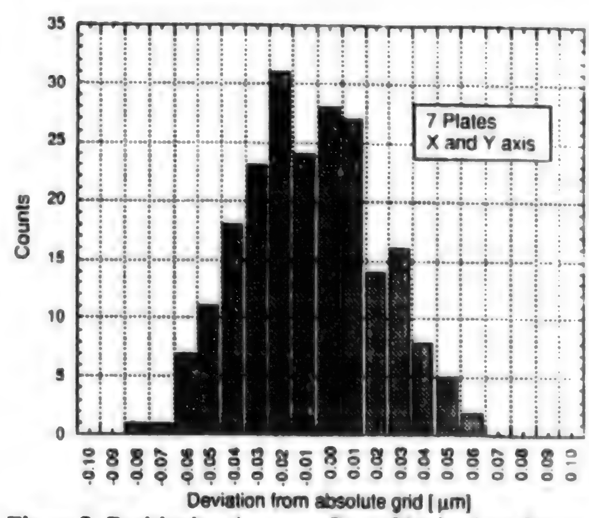


Figure 8. Positioning Accuracy Data Obtained on Seven Substrates Measuring Six-inches Square and 0.25-inches Thick

Exposure Evaluation

We evaluated test mask exposure performed using an i-line stepper (CANON i3). We compared the focal depth (Table 3) and exposure latitude (Table 4) used to make holes in an ordinary mask and a half-tone phase-shifting mask. Photo 3 shows the resist images for both types of mask. From this comparison, it is plain that the exposure latitude for the half-tone phase-shifting mask is larger than those for the ordinary mask. The addition of positive bias to the dimensions of the half-tone mask helps diminish the resist borders or fringes generated around the holes during dense placement. Because half-tone phase-shifting masks are so readily available nowadays, we are pushing full steam ahead on user evaluations.

Table 3. Scope of Defocus at Hole Opening

σ	Dose [mJ/cm²]	Defocus Range of the Hole Opening [μm]			
		HT-PSM		Normal Mask	
		0.4*	0.36*	0.4*	0.36*
	330	1.6	0.6	1.0	—
0.6	370	1.8	1.0	1.4	0.2
	410	2.2	1.4	1.4	0.6
0.3	330	2.8	2.6	1.4	—

Courtesy of Canon Inc.

* Mask size on a wafer: NA = 0.60, resist: PFI-26, resist thickness: 1.085μm; Stepper: ANON i3

Table 4. Exposure Latitudes for Half-tone Phase-shifting Mask

σ Dose [mJ/cm²]	Hole size [μm]					
	0.6			0.3		
	330	370	410	290	330	370
HT-PSM	0.34	0.37	0.41	0.36	0.37	0.38
Normal mask	0.31	0.37	0.40	0.33	0.37	0.39

Courtesy of Canon Inc.

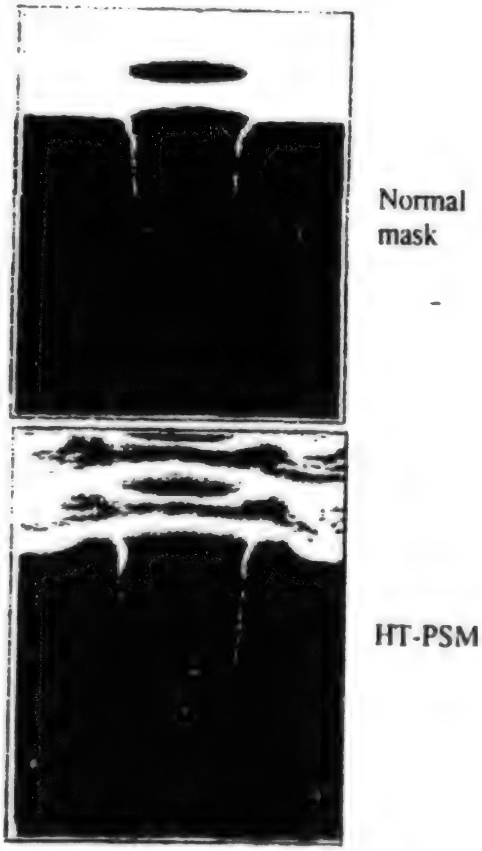


Photo 3. Cross Section of Holes

Defect 'nspections

Defect inspections are performed using a 239HRL-PS made by the KLA Co. We have completed evaluating defect detection sensitivity using a die-to-die comparison method, and received good operational results. We are now performing evaluation work using a die-to-database comparison method.

Defect Repair

Defect repair on half-tone phase-shifting masks uses practically the same repair methods used to fix defects on ordinary masks. Black defects (black spots and protuberances) can be removed using laser irradiation. And we've learned that white defects (pin holes and cavities) can be repaired by using a focused ion beam to cover them with a carbon film. There are no adverse effects from the halos of the carbon films, and we've determined that the optimum film thickness for achieving the screening effect is roughly 150nm. We also used exposure tests to examine the transfer characteristics of defects. We've determined that holes do not need repairing if their dimensions are within +/- 10 percent of the design value in the focal positioning range (-0.6μm-0.6μm). Table 5 compares the dimensions of detectable defects and repair-required defects. The results of this comparison confirmed that detectable defects are smaller than defects requiring repair. Figure 9 diagrams the recovery of exposure characteristics by means of repairing a cavity-type defect.

Table 5. Comparison of Detectable Defect Dimensions and Repair-Required Defect Dimensions (Units: m)

Defect Category	Minimum Detectable Defect Size	Minimum Intolerable Defect Size
Pinhole	0.8	1.0
Intrusion	0.4	0.5
Pinspot	0.3	0.4
Extrusion	0.4	0.5
Hole size: 0.4μm design rule, λ = 365nm, NA = 0.57		

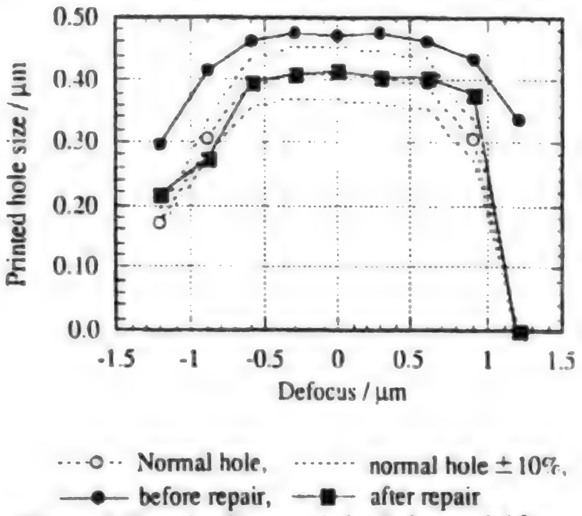


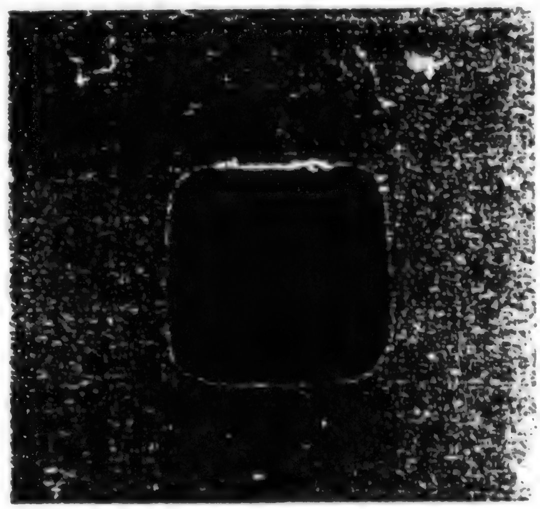
Figure 9. Transfer Characteristics Before-and-After Repair of a Cavity Defect

Quality Assurance

Two quality assurance items peculiar to half-tone phase-shifting masks used with g-line and i-line energies are transmittance and phase difference. Off-the-shelf spectral transmissometers can be used to measure transmittance if the measurement area isn't limited to the micron regime. When it comes to phase difference, we measure this using the Lasertech IPM11 phase difference measuring device, which is capable of measuring this difference at 633nm. The results obtained from these measurements are converted to g-line or i-line values in accordance with a conversion curve previously determined experimentally. A number of reports have been published on instruments capable of directly measuring phase difference at g-line and/or i-line energy levels,[12,13] and we are looking forward to good results.

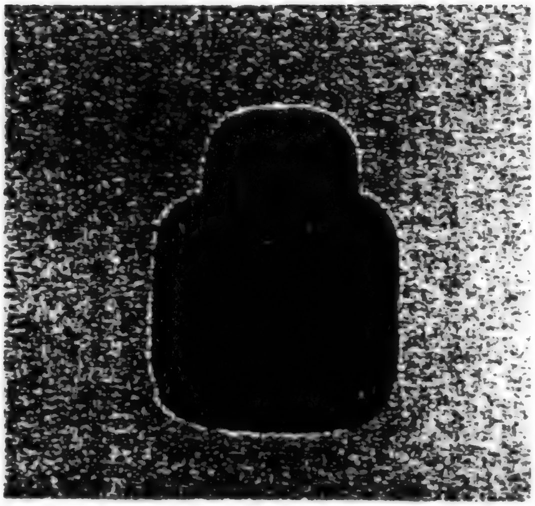
At Dainippon Printing, we apply the same quality assurance standards to our half-tone phase-shifting masks that we do to our ordinary masks to produce defect-free products.

Before Repair

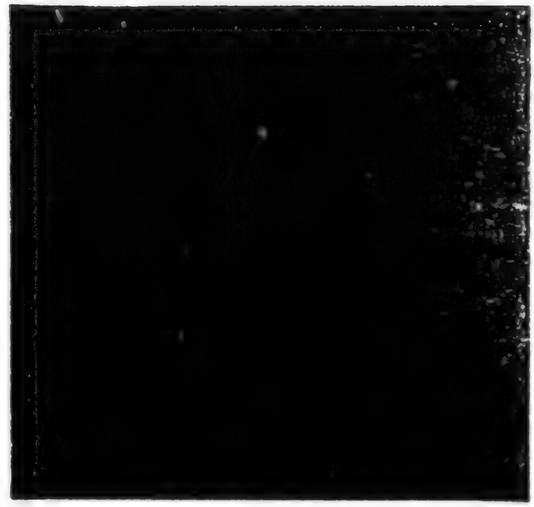


After Repair

Photo 4. Example of Repairing a Protuberance Defect



Before Repair



After Repair

Photo 5. Example of Repairing a Cavity Defect

3.4 Other Types of Phase-shifting Masks

All of the other types of phase-shifting masks are still in the prototyping stage and thus immature as far as mass production technologies are concerned. If the market evaluates one of these types of masks as possessing inherent advantages, then development of that type of mask will most likely accelerate. We are looking forward to demand for these masks from numerous users. The following is a brief description of each of these types of masks.

a) Auxiliary Shifter Phase-shifting Mask

With this type of mask, one or two pairs of auxiliary shifter patterns are formed near the main pattern to increase that pattern's resolution. These masks are used to image contact holes and lines. There have been reports on auxiliary shifter masks for contact hole use,[1] but because this type of phase-shifting mask will be competing with the half-tone mask in this field, it (auxiliary shifter mask) is not expected to find very widespread application. The auxiliary shifter mask is also effective at forming isolated lines, but it is not yet clear whether there is enough market demand for this application to prompt the mask makers to solve the problem of non-resolution.[Note 1]

b) Chromeless Phase-shifting Mask

Chromeless masks offer the advantages of using only shifter patterns that are below resolution limits, and can be formed from a single phase shifter layer. However, the mask image and resist image tend not to be the same with chromeless phase-shifting masks, making design work impossible and giving rise to the problem of non-resolution.

c) Rim Phase-shifting Mask

This type of phase-shifting mask will compete with the half-tone mask for use in imaging contact holes. Means of precisely controlling rim width must be dealt with.

d) Shifter Shading Phase-shifting Mask

This is a combination of a chromeless and rim phase-shifting mask. As such, it too must deal with the problem of precisely controlling rim width.

4. Conclusion

Half-tone phase-shifting masks have matured to the point where mask makers will start producing them in volume.

Acknowledgments

I would like to thank Senior Researcher Takahashi of Canon's Semiconductor Device Division for carrying out exposure evaluations for us. And since this report borrowed heavily from Papers I, II and III of Dainippon Printing's Photomask Japan '94, I would like to take this opportunity to thank the authors of those papers for their contributions to this report.

Footnote

Note 1: This problem arises when a pattern is formed that is not optically resolvable, for both quantitative (increased data volume, writing time and inspection time) and qualitative (design, processing and inspection difficulties) reasons.

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Technology for Practicalizing Excimer Laser Resists

94FE0815E Tokyo PRESS JOURNAL in Japanese 24 Jun 94 pp 33-43

[Article by Naomichi Abe (phonetic) of the Process Development Department, Electronic Device Division, Fujitsu Corporation]

[FBIS Translated Text]

1. Introduction

The integration level of integrated circuits (IC) has been increasing four-fold every three years, and is expected to continue progressing at this pace in the future. The downscaling of IC geometries has been proceeding apace, to the point where we are on the verge of practicalizing 0.3μm feature sizes. Despite the argument currently taking place as to whether 0.3μm patterning should be carried out using i-line energy (365nm) or krypton-fluoride (KrF) excimer laser radiation (248nm), the fact remains that the relationship between light wavelength and resolution requires that we make the switch from i-line to KrF excimer laser technology, meaning that we must establish a KrF excimer laser exposure process in order to realize 0.3μm geometries.

But developing such an excimer laser process carries with it some major problems from the standpoint of the resist process. One such problem has to do with chemically-amplified photoresist. The novolak-based resists used to date cannot be applied to the KrF excimer laser exposure process due to their low transmittance to KrF excimer laser radiation. Chemically-amplified resist is therefore seen as the most likely candidate to replace novolak resists for use with excimer lasers. However, the principle upon which chemically-amplified resist operates differs completely from that of novolak-based formulations, giving rise to technical problems peculiar to chemically-amplified resist which will have to be dealt with before it can be practicalized for commercial use.

One such technical problem currently being addressed has to do with the effects of substrate reflection. Substrate reflectance is generally on a scale with shorter wavelengths. This fact, taken together with the downscaling of pattern dimensions, creates a major technical problem from the standpoint of the resist process when light reflects off of the substrate during KrF excimer laser exposure.

This paper focuses on these resist-oriented problems, and introduces the results of a number of technological studies aimed at practicalizing a KrF excimer laser exposure process.

2. Chemically-Amplified Resist

Chemically-amplified resist is comprised of a polymer and an acid-generating agent (PAG). The PAG reacts to the radiation during exposure, generating an acid. This acid then serves as a catalyst during post exposure bake (PEB), causing a thermal reaction in the polymer that changes its (polymer's) solubility. Extremely small amounts of the generated acid acting as a catalyst can cause reactions in large amounts of polymer. That is, the acid generated from one photon can cause several thousand polymer reactions. The term chemically-amplified resist comes from this kind of amplifying action (Figure 1). Because conventional novolak-based resists generate one reaction per photon of exposing energy (this ratio, which is referred to as quantum yield, is actually less

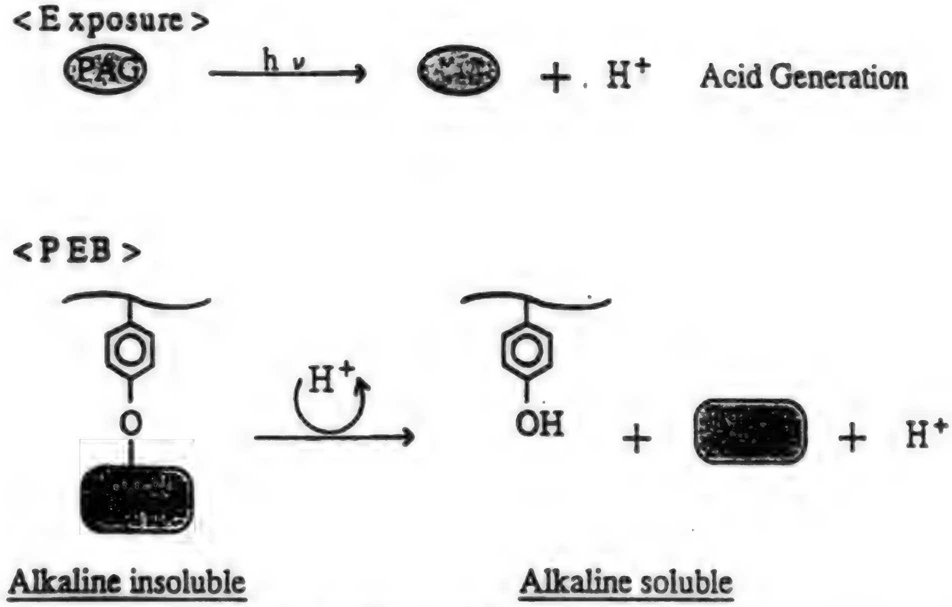


Figure 1. Principle of Chemically-Amplified Resist

than one for one), chemically-amplified resists are extremely advantageous from the standpoint of sensitivity. And because the chemically-amplified reaction mechanism allows for a wide selection of polymers, this type of resist is the leading candidate for a KrF excimer laser resist that requires polymer transparency.[1] However, because the reaction mechanism is fundamentally different from that of conventional resists, chemically-amplified resist poses resist- and process-oriented problems not found in conventional resists. The following are some representative examples of these problems, and the results of tests designed to come up with countermeasures to them.

(1) Resist Material

There are resist materials available today that possess the basic performance needed for practical application in the fabrication of 0.3μm patterns. These materials are inherently sensitive to radiation, and are easily made highly sensitive using the principle of chemical amplification, with 20-40mJ being common. They also offer the resolution necessary for 0.3μm feature sizes, and can assure the 1.5μm of depth of focus (DOF) required for volume production (Figures 2 and 3).

The problem is how to deal with such drawbacks as T-tops and post exposure delay (PED) inherent in chemically-amplified resist. We will cover these problems in detail in the following section on the resist process, but these problems are rooted in the principle of chemically-amplified resist, and will be impossible to solve from the aspect of the resist material alone.

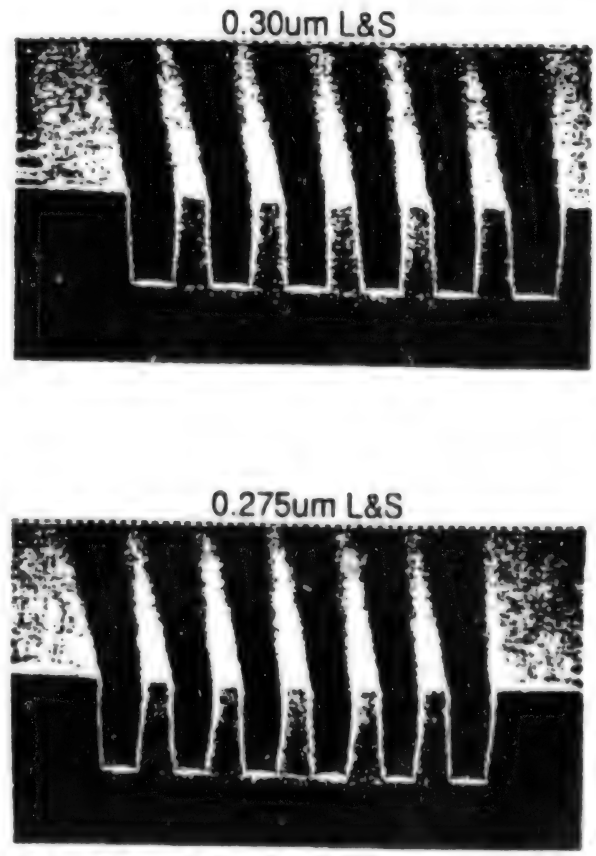


Figure 2. Resolution With Excimer Resist (NA = 0.45)

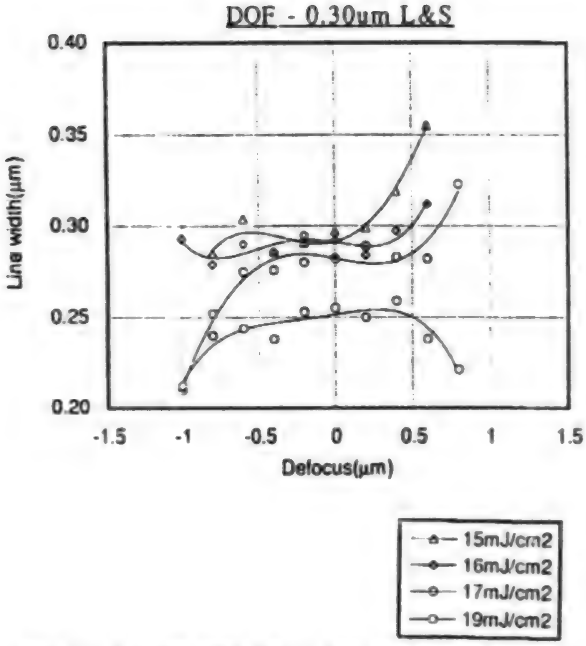


Figure 3. DOF With 0.3µm Line & Space Pattern

(2) Resist Process

With chemically-amplified resist, exposure simply generates the acid that will act as a catalyst in the polymer reaction; the actual reaction is generated during the heating process following exposure. Therefore, how best to control the process from exposure through PEB is an extremely important point. This section takes up the technical problems inherent in chemically-amplified resist in the order they appear in the resist process, and discusses the results of process-oriented studies aimed at dealing with these problems.

[1] PEB Temperature Control

As pointed out above, with chemically-amplified resist, the polymer itself does not change during the exposure process, but rather, the polymer reaction takes place during the PEB process thereafter. Therefore, whereas PEB is carried out with novolak-based formulations simply to reduce standing wave patterns in the sidewalls of resist patterns, with a chemically-amplified resist, PEB controls the polymer reaction, thereby playing a direct role in the formation of the resist pattern dimensions.

Figures 4 and 5 provide data on test results that demonstrate this fact. As can be seen from this data, whereas the pattern dimensions in a novolak-based resist changed very little if at all in response to fluctuations in PEB temperature, the dimensions of patterns imaged in a chemically-amplified resist underwent major changes in line with changes in PEB temperature. The results of these tests indicated that PEB temperatures must be controlled to within 0.3°C for patterns in the 0.35µm regime. This means that special high-precision heating stages must be developed for use with chemically-amplified resists since current off-the-shelf heating apparati do not possess adequate heat control capabilities.[2]

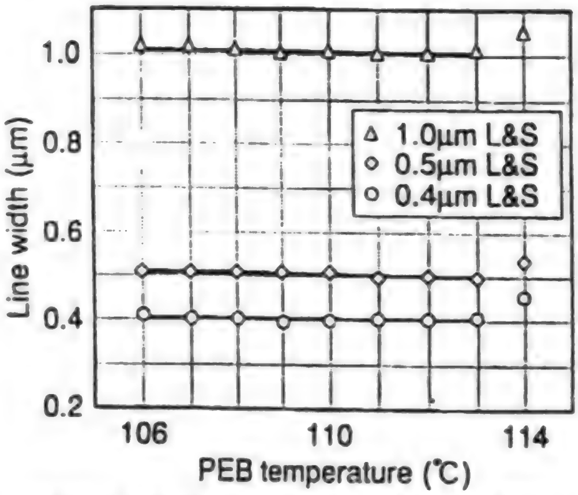


Figure 4. PEB Temperature Dependence of Pattern Dimensions Imaged in i-Line Novolak-Based Resist

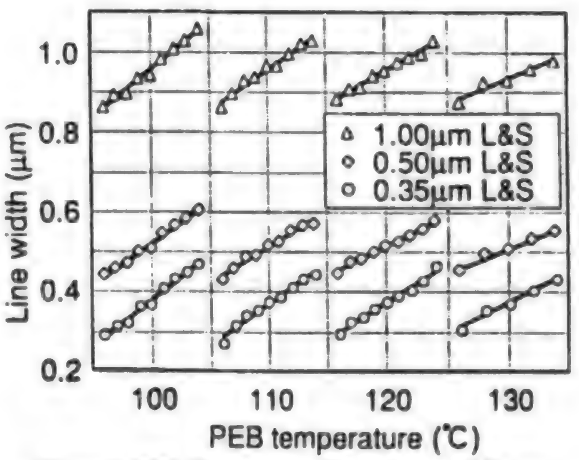


Figure 5. PEB Temperature Dependence of Pattern Dimensions Imaged in Chemically-Amplified Negative Resist

[2] Problem of T-tops With Positive Chemically-Amplified Resist

There is more demand for chemically-amplified positive resists than for similarly amplified negative resists due to the advantages the former possesses when it comes to making holes, but chemically-amplified positive resists suffer from a number of technical problems that must be solved before they can be put to practical use. The biggest of these problems is something called T-tops, which result from a thin layer formed on the surface of

the resist that does not dissolve in the developing solution. This phenomenon is peculiar to chemically-amplified positive resists, and the extent of T-top formation depends on the length of PED (time between end of exposure and start of PEB) and the environment in the clean room. The cause of T-tops is believed to be the ammonia, amines and other basic substances in the atmosphere that react with the acid generated during exposure, neutralizing it and causing a deficiency of acid on the surface of the resist (Figure 6).[3]

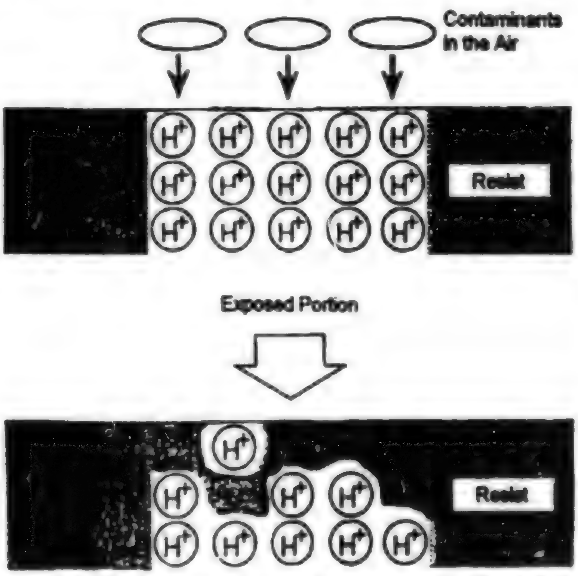


Figure 6. Cause of T-tops (Surface insoluble layer)

It would be nice if this problem could be solved by improving the resist materials themselves, and resist manufacturers have been working hard to do just that, but although they have succeeded in altering the extent to which T-tops are formed, no one has come up with a material that eliminates T-top formation altogether. From our explanation of the T-top mechanism above it is clear that the resist process should be carried out in an environment free of amines and other basic substances. This would enable us to readily deal with the problem of T-tops from a process-oriented approach. One approach is to cover the chemically-amplified positive resist with a protective layer that will prevent the formation of T-tops. This method calls for spin coating an organic resin material onto the resist to protect it (resist) from coming in contact with the amines and other basic substances in the surrounding air. The effect of this protective layer differs with the type of organic resin applied, but non-polar resins seem to be the most effective.[4]

Another approach is to carry out the processes from exposure through development in an environmentally-controlled atmosphere. This is done by arranging the stepper and coater/developer equipment to operate in line, and then pumping chemically-filtered air into the equipment (Figure 7). By so doing, the concentration of ammonia in the air can be maintained at below 1ppb. Leaving exposed wafers in an ordinary clean room atmosphere (ammonia concentrations = several ppb) for 30 minutes prior to subjecting them to PEB results in the formation of severe T-tops, but no T-tops form when similar wafers are left in an environmentally-controlled atmosphere for 30 minutes (Figure 8). Of the two anti-T-top measures just discussed, the environmentally-controlled atmosphere approach is less costly and involves fewer processes, leading us to believe that this approach will become the main focus of future studies.[5]

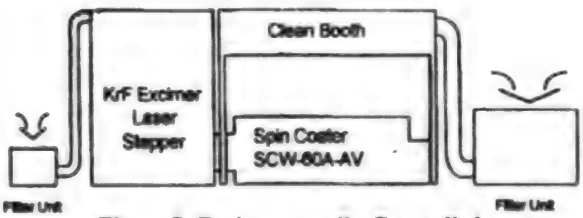


Figure 7. Environmentally-Controlled Exposure-to-Development System

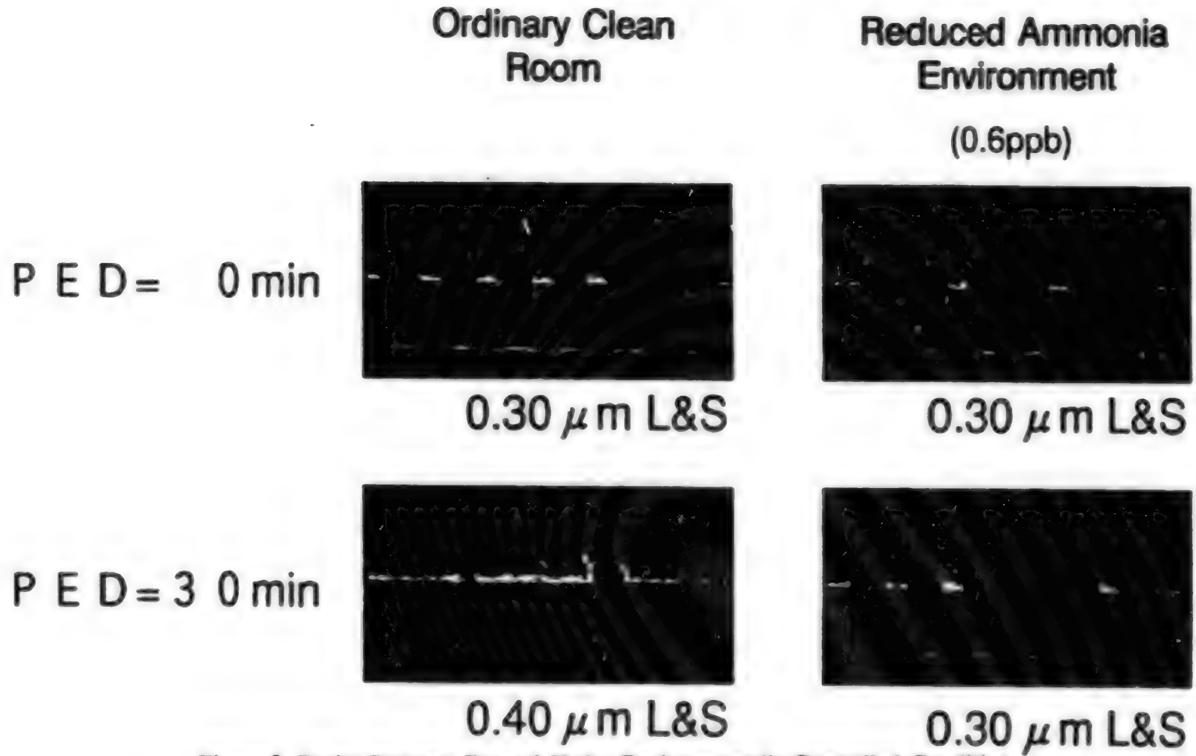


Figure 8. Resist Patterns Formed Under Environmentally-Controlled Conditions

[3] Substrate Boundary Pattern Deformation

With certain substrates, chemically-amplified positive resists exhibit blind-over-edging, and negative resists exhibit undercutting at the boundary between the substrate and the resist. These phenomena are marked when chemically-amplified resists are applied to silicon nitride (SiN) and spin-on-glass (SOG) substrates. The causes of these phenomena have yet to be determined, but are believed to be the result of insufficient acid generation at the substrate boundary during exposure, making them once again problems inherent in chemically-amplified resists. Since these phenomena are dependent on the substrate, the most effective means of dealing with the problem would seem to be to enhance the condition of the substrate surface.

Let's look at a method for dealing with the phenomenon of undercutting in patterns imaged on chemically-amplified negative resist applied to SOG substrates. When undercutting occurs at the substrate boundary, in a worst case scenario, the pattern collapses. However, when chemically-amplified negative resist patterns are baked at 270°C following hexamethyldiazane (HMDS) processing, undercutting does not occur (Figure 9).[6] Therefore, using one means or another to alter the condition of the substrate surface in this way seems to be an effective method for combatting the problem of undercutting. The same approach works well with patterns imaged in negative resist coated on SiN substrates when O_2 plasma processing is employed.[7]

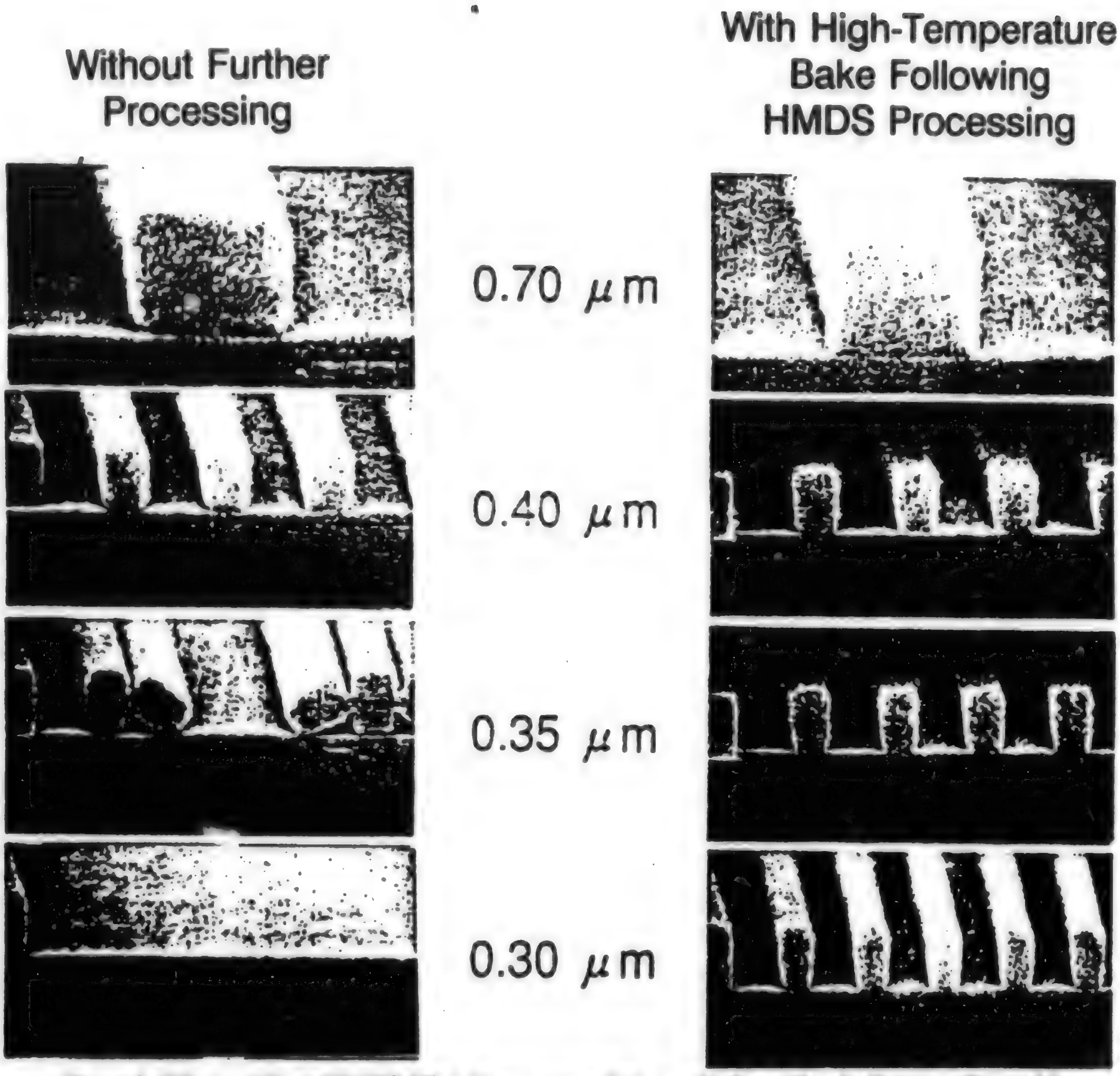


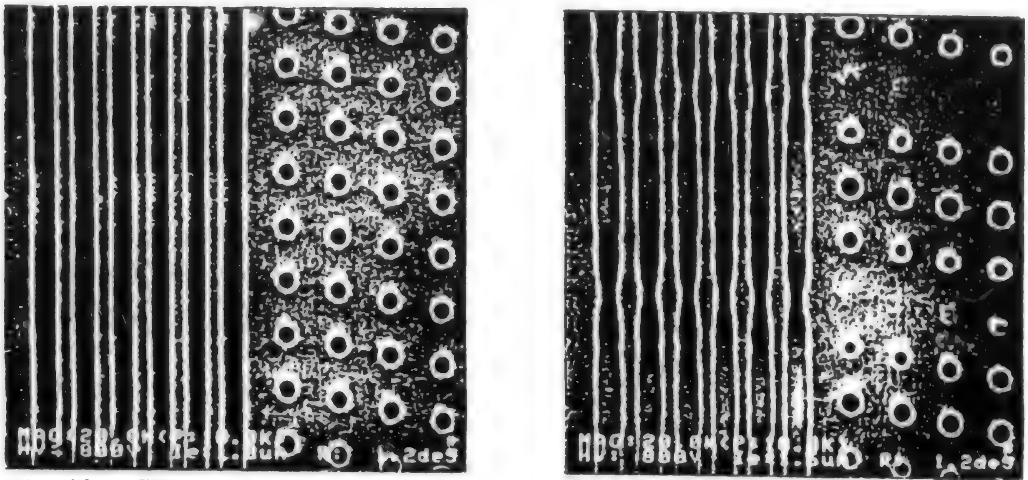
Figure 9. Effects of Post-HMDS High Temperature Bake on Undercutting in Patterns Formed in Chemically-Amplified Negative Resists Coated on SOG Substrates

3. Impact of Substrate Reflection

The shorter wavelength of the KrF excimer laser results in greater substrate reflectance than is exhibited with i-line energies (Figure 10). For example, the reflectance of Si substrates to KrF radiation is twice what it is for i-line radiation. This exacerbates problems such as dimensional fluctuations resulting from differing coating thicknesses caused by multiple interference, and halation caused by irregular reflection.

Figure 10. Reflectance at the Boundary Between the Substrate and the Resist

	i-Line	KrF
Si	22%	51%
poly Si	35%	48%
WSi	31%	31%
TiN	10%	14%



(a) with a-C:H (b) without a-C:H

Figure 11.

In the past, these problems were dealt with by adding dyes to the resist. However, adding dyes to a resist decreases its transmittance, i.e. impairs the enhancement of the resist, and cannot be considered a fundamental solution.

There have been studies in recent years, therefore, on antireflection coatings (ARC), which are coatings applied under the resist to absorb radiation during imaging. We would like to discuss one such ARC here called a-C. a-C has extremely high absorbability, and just a several hundred angstrom-thick layer of a-C provides more than sufficient antireflection capabilities. Also, because a-C layers are formed via plasma CVD or sputtering processes, they provide much better coverage of irregularities than do spin-coated polymer ARCs.

Figure 11 shows the antireflection effects of using a-C. As you can see, the pattern imaged over a-C is completely without dimensional fluctuations brought on by multiple interference. The thickness of the a-C layer used here was roughly 300 angstrom, which made removal of the a-C layer during etching very simple.[8],[9]

4. Conclusion

Two major points in the practicalization of an excimer laser resist will be chemically-amplified resist materials and processes, and the impact of substrate reflection. The following are our conclusions regarding these factors.

(1) Chemically-Amplified Resists

The basic performance of resist materials has reached the level where they can be considered practical for imaging 0.3μm patterns, but chemically-amplified resists still suffer from a number of peculiar problems. These problems have their basis in the chemically-amplified resist principle, and therefore cannot be dealt with solely in terms of the resist material, making process-oriented studies and controls extremely important. These process-oriented measures include: (1) control of PEB temperatures to define pattern dimensions; (2) environmental control to combat T-tops; and (3) control of substrate surfaces as a means of preventing blind-over-edging and undercutting.

(2) Impact of Substrate Reflection

In general, the reflectance of excimer lasers during exposure processing is greater than that of i-line radiation. And because this poses a more significant problem to patterning, antireflection techniques become imperative. One such leading method is the formation of an antireflection coating using a-C.

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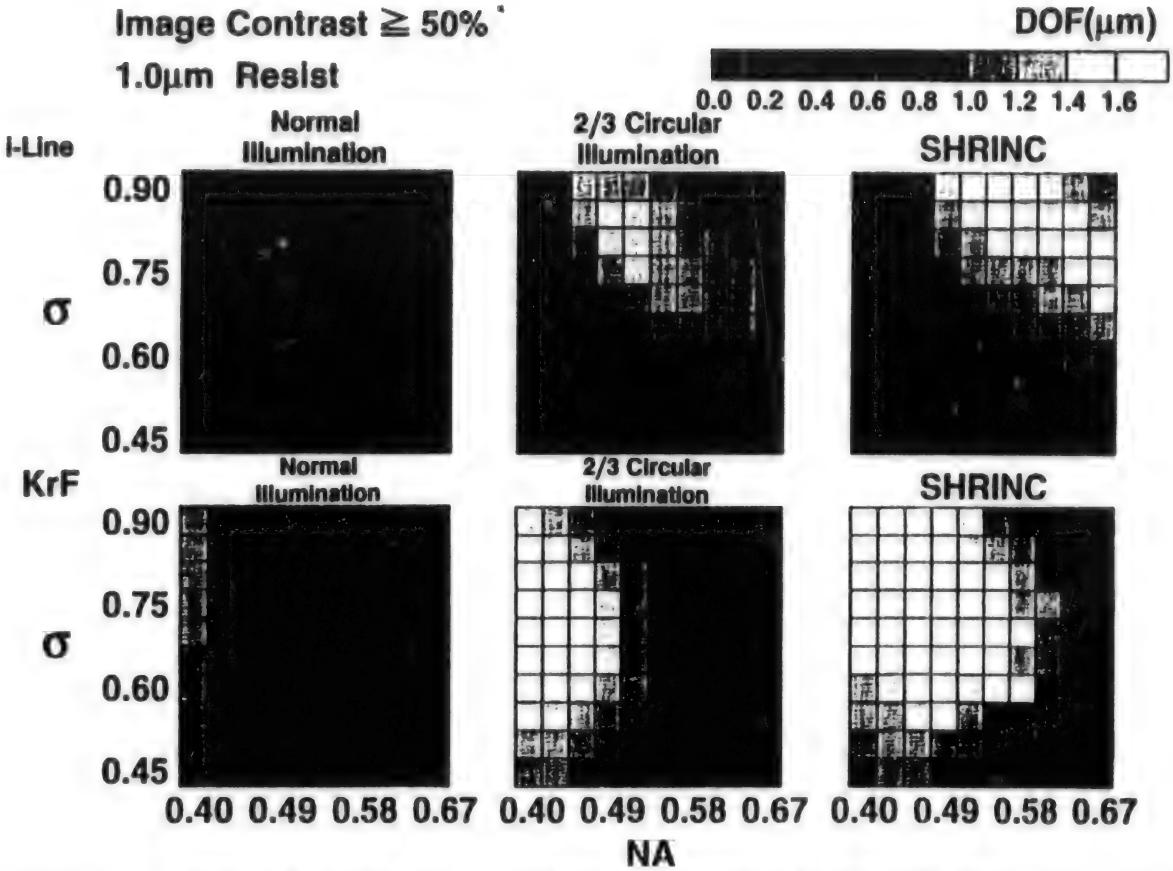

Figure 1. DOF for 0.30μm Line and Space Pattern (Results of Simulation Tests)

Reduction Lens Steppers for Use in 0.3μm Lithography: Problems and Countermeasures

94FE0815F Tokyo PRESS JOURNAL in Japanese 24 Jun 94 pp 45-56

[Article by Seiro Murakami of the Precision Instruments Design Department No 1, Nikon Corporation]

[FBIS Translated Text]

1. Introduction

Reduction lens steppers (hereafter referred to simply as "steppers") are the principal lithography tools used in the fabrication of semiconductor devices today. Steppers were introduced into production operations about the time memory integration, typified by dynamic random access memory (DRAM), reached 64K, and these instruments have continued to play a major role in the semiconductor manufacturing process right up to the volume production of 16M devices. They are also expected to play a central role in the future in the fabrication of 64M and larger semiconductor devices, which will feature line widths in the 0.4μm-0.3μm regime. This paper is designed to introduce the latest in i-line and krypton-fluoride (KrF) excimer laser stepper technology, and to point out some of the problems facing these steppers when it comes to 0.30μm lithography technology, as well as certain solutions to those problems.

2. Projection Optical Systems

2.1 Imaging Capabilities

First of all, I'd like to call your attention to Figure 1, which shows the depth of focus (DOF) predicted via simulations of imaging capabilities for 0.30μm line and space (L&S) patterns (using i-line and KrF excimer laser wavelength energies). The results are presented in three blocks, i.e. normal, circular and oblique (SHRINC[2]) illumination, for the parameters numerical aperture (NA) and resolution (σ) for each wavelength. DOF was determined by subtracting the equivalent of the resist thickness from the focal range obtained when aerial image contrast is better than 50 percent. As can be seen from these graphs, it is impossible to achieve a DOF of greater than 1μm with i-line technology under normal illumination, but employing circular and SHRINC illumination make it possible to obtain 1.5μm or larger DOF with i-line energy. By contrast, 1.4μm DOF can be achieved under normal illumination using KrF excimer laser technology.

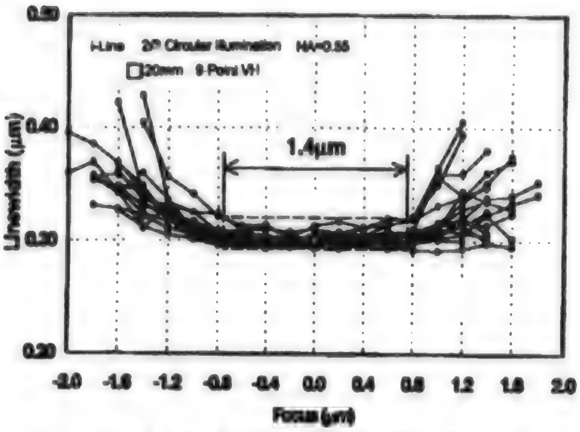

Figure 2. CD-Focus at 0.30μm (Test Data)

Next, Figure 2 furnishes examples of test results on actual resist patterns imaged using i-line energy. For these tests, two-thirds circular illumination was employed, and the projection lens was set at NA = 0.55. The figure diagrams critical dimension (CD) focus data at nine points within the exposure area from which a figure of 1.4μm was derived as the DOF for a linewidth variation tolerance of 0.03μm (10 percent of 0.3μm).

Resolution of 0.30μm is possible as described above. To practicalize this approach, steppers will have to make the image surface and illuminance within the exposure field more uniform, and to set the optical parameters (NA, σ) in accordance with the shape of the pattern. On the operations side of the process, it will be important to manage reticle dimension variance and to optimize the resist. Also, we are discussing L&S patterns here, but the DOF will have to be made larger for isolated patterns. The FLEX[3)] and pupil filtering[4),5)] methods have been proposed for the imaging of contact holes in particular, and the latter (pupil filtering technology) is at the stage where studies are being carried out to practicalize it.

2.2 Field Size

For the mass production of semiconductor devices, the field size of the transfer equipment must be large enough to process two or more chips. Steppers currently in widespread use offer a field size of 22 x 22mm, which does not pose a problem in the volume production of 64MDRAM. However, this field size will not be able to cover two chips with integration levels of 256M each once we start mass-producing devices with feature sizes of 0.30μm and smaller. As shown in Figure 3, increasing the field of the lenses will raise costs considerably. Cost will become an especially serious problem when it comes to the optical materials required for the deep ultraviolet (DUV) regime. We feel that new concepts (i.e. scanning, stitching) are needed to fulfill the need for increased field size.

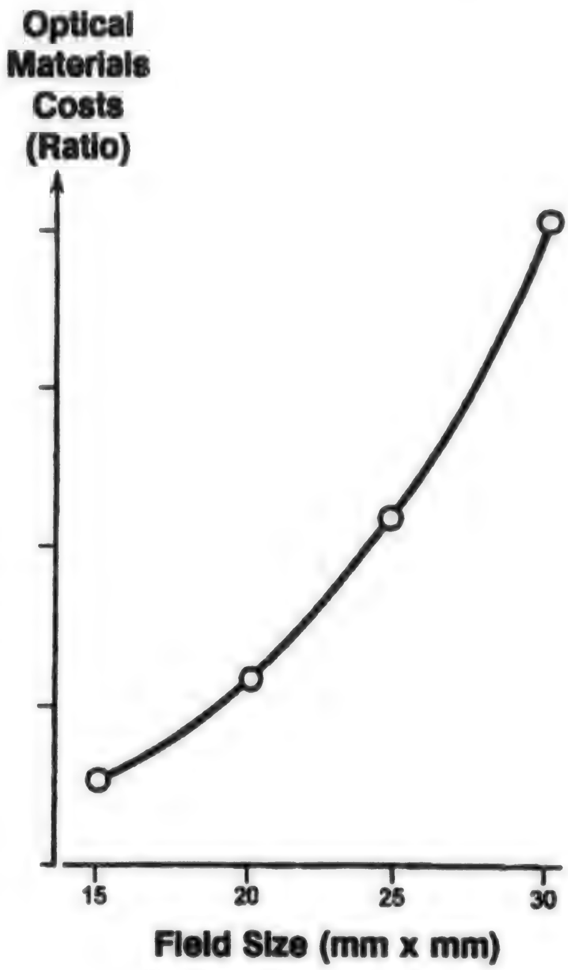

Figure 3. Field Size Versus Optical Material Costs

3. Alignment Systems

Generally speaking, overlay accuracy (total overlay) must be less than one-third of the design line width. Figure 4 provides a bar graph matching the total overlay budgets for linewidths of 0.4μm (130nm) and 0.3μm (100nm). Let's devote a little time here to dividing each of the error budgets into equipment-related and process-related budgets, and talk about recent stepper improvements and developments aimed at lowering these budgets.

3.1 Equipment Performance

Simultaneous baseline measurement has been introduced as a means of improving the accuracy of measuring the baseline portions of total overlay budgets. Figure 5 illustrates the concept behind this approach. In the past, baseline measurements for reticle and wafer

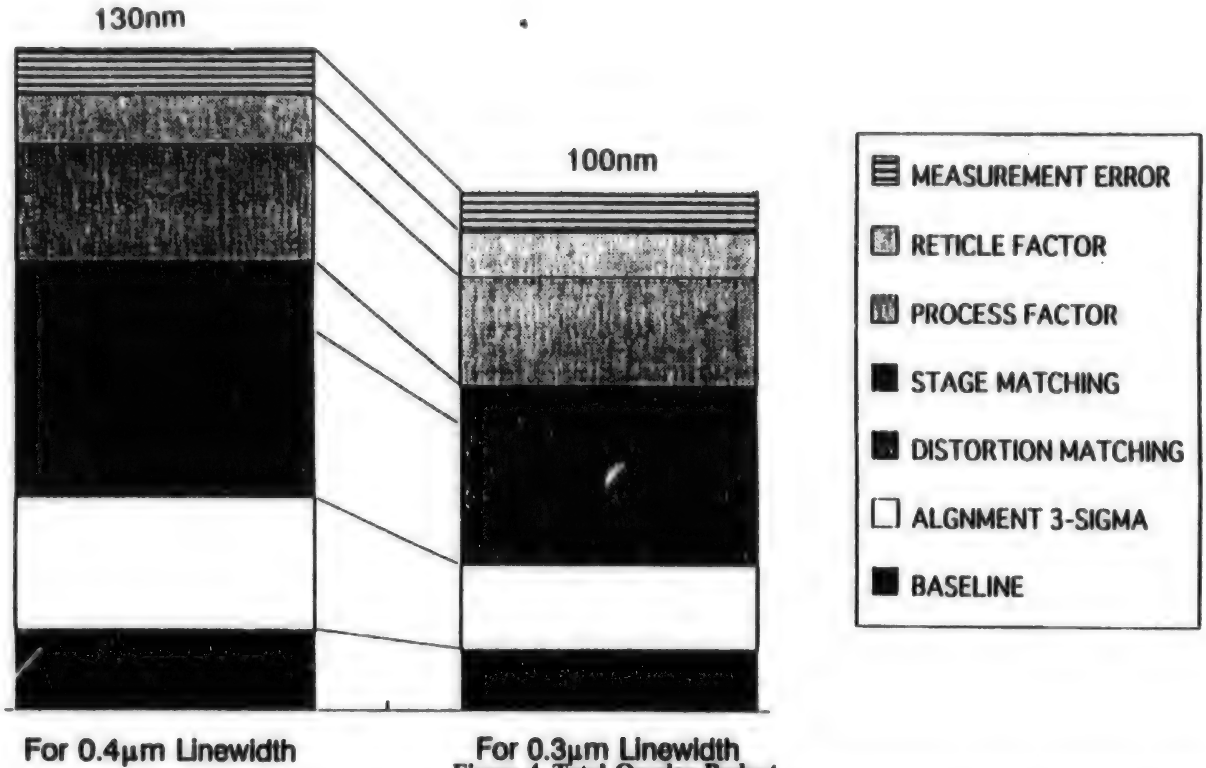

Figure 4. Total Overlay Budget

alignment sensor locations were taken separately while the stage containing the fiducial marks for measurement purposes was moved. Each of these measurements was therefore susceptible to the effects of interferometer fluctuations, drift and stage accuracy. Simultaneous baseline measurement, introduced as a means of improving these points, can simultaneously measure the locations of the reticle and wafer alignment sensor(s) via an improved fiducial marking scheme, thus reducing the effects of the aforementioned error factors.

Next, "Alignment Sigma-3" refers to improvements made to the laser interferometer mounted to the wafer stage. The first of these involved installing an interferometer optical path air conditioning system to reduce interferometer fluctuations by optimizing air conditioning in the interferometer optical path. Figure 6 presents graphic data showing how improving the uniformity of the temperature in the optical path using air conditioning achieved stable interferometer fluctuation signals of less than several nm. Another improvement involved numerically correcting the curvature of the movable mirror(s) that comprise the interferometer, thereby reducing exposure shot layout errors.

3.2 Process-Related Errors

Wafer process-related errors, or "Process Factors," account for a large percentage of the overall overlay budget. First of all, we must precisely detect alignment marks under various process conditions. Three sensors (LSA, FiA and LiA), each operating on different principles, are available on the NSR, making it possible to select the optimum sensor for each process. And deformations produced in the wafer process result in errors that cannot be ignored. A new alignment compensation sequence has been introduced to deal with these errors. A

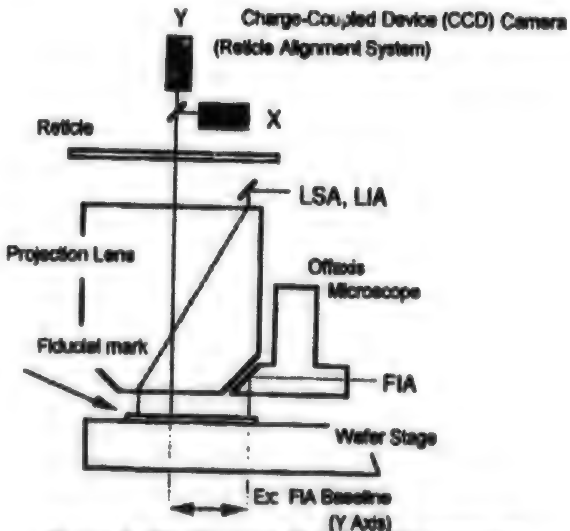

Figure 5. Simultaneous Baseline Measurement

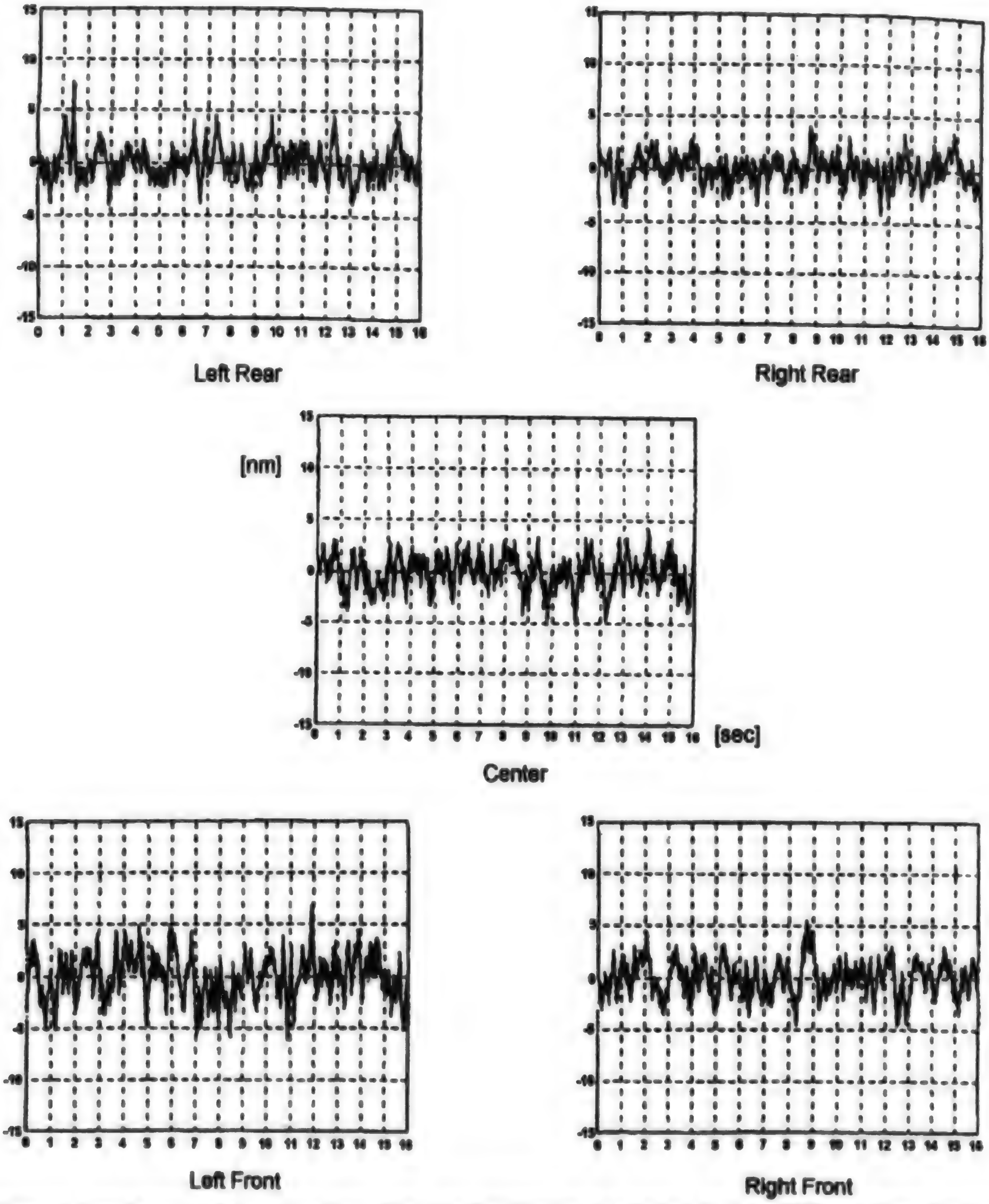

Figure 6. Interferometer Fluctuation Data After Air Conditioning the Optical Path (at Different Stage Positions)

weighted EGA sequence was also developed to change the weight of alignment correction at each exposure shot. A chip magnification compensation sequence was developed, too. This sequence feeds back wafer scaling data to lens magnification to correct for chip expansion and contraction.

Other budget items that require our attention are reticle manufacturing errors, or "Reticle Factors," and registration errors, or "Measurement Factors." To improve the former, we must enhance the length dimension accuracy of current electron beam writing systems in particular. As for the latter, we'll have to conduct system-oriented studies, to

include studies aimed at enhancing the self-measurement functions on steppers.

4. Conclusions

0.3μm lithography is possible with both i-line and KrF excimer laser lens steppers. Selecting between i-line technology and KrF excimer laser technology should not be based on judgments regarding the equipment alone, but rather, should include such factors as developments in device and resist processes and equipment investment. As far as the steppers themselves are concerned, efforts will have to be made to enhance the performance of these tools no matter which technology is selected, especially when it comes to improving the uniformity of the image field (X,Y,Z) of imaging systems, and to reducing the matching errors that occur in alignment systems.

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0.3μm Lithography

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[FBIS Translated Text]

Summary

Recent developments in the field of semiconductor integrated circuits (ICs) have been phenomenal, so much so that it is now appropriate to call these ICs integrated electronic systems. The scale of these systems has grown from large scale integration (LSI) to very large scale integration (VLSI), and will soon reach ultra large scale integration (ULSI), whereby over a million elements will be packed onto a single chip. By the beginning of the 21st Century, we can expect to see ULSI systems which, in and of themselves, comprise electronic equipment systems. This progress has had a significant impact on society. In fact, it would not be overstating the case to say that it has generated today's advanced information society. The development of the means to transmit images and communicate data has reduced the relative size of our planet, and increased the need for advanced information processing on a global scale. And it has been the IC that has supported this advancement on the hardware side. Moreover, the semiconductor industry has accelerated the downsizing of the computer, to the point where it has become difficult to distinguish between computers slated for the consumer market and those designed for industrial use. And hand in hand with the diversification of everyday lifestyles, the merging together of audio-visual and telecommunications technologies is expected to give rise in a few years to a multimedia industry that will create a market of immense proportions. The driving force behind this industry and the market it generates will be super ULSI called "systems on silicon" built around cores comprised of microprocessors. But to realize all this, the semiconductor industry will have to pursue downscaling even more than it has to date. The actual processing dimensions required will be less than 0.3μm, or well below the half micron level.

Recently, the semiconductor industry has been emphasizing low-cost approaches that take state-of-the-art technologies and develop them into next generation technologies, all the while maintaining productivity at volume levels. However, lithography technology at the research and development level has caught up to design rules, and we have reached the point now where a major technological and economical breakthrough is required.[1]

One of the motivating forces in realizing VLSI devices has been ultraviolet radiation and the reduction-projection exposure equipment (steppers) that generate and control this radiation, i.e. advancements in microprocessing technologies using photolithography techniques. Major factors involved in enhancing the resolution of photolithography technology are increasing the numerical apertures (NA) of the steppers, shortening the wavelength of the exposing energy and improving the resolution of the resists. At present, microprocessing techniques have been developed that have made it possible for g-line (436nm wavelength) steppers to image half-micron patterns, for i-line (365nm wavelength) steppers to image 0.4 micron patterns, for krypton-fluoride (KrF) (248nm wavelength) excimer lasers to image quarter-micron patterns, and for argon-fluoride (ArF) (193nm wavelength) excimer laser lithography to image sub-quarter-micron patterns. Expectations are running high for excimer lithography.2) But for economic reasons, research and development aimed at extending i-line lithography capabilities is also quite prevalent. Under technological and economic conditions such as these, we are being pressured to select, based on major technological strategies, that lithography technology capable of handling the fabrication of both ULSI memory and logic devices.

In this report, we discuss 0.3μm lithography capable of dealing with ULSI logic by comparing i-line lithography

to new approaches[3,4] for improving pattern and alignment accuracy in particular in order to practicalize the highly-anticipated KrF excimer laser technology as the lithography technology for next-generation devices.

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0.3µm Lithography

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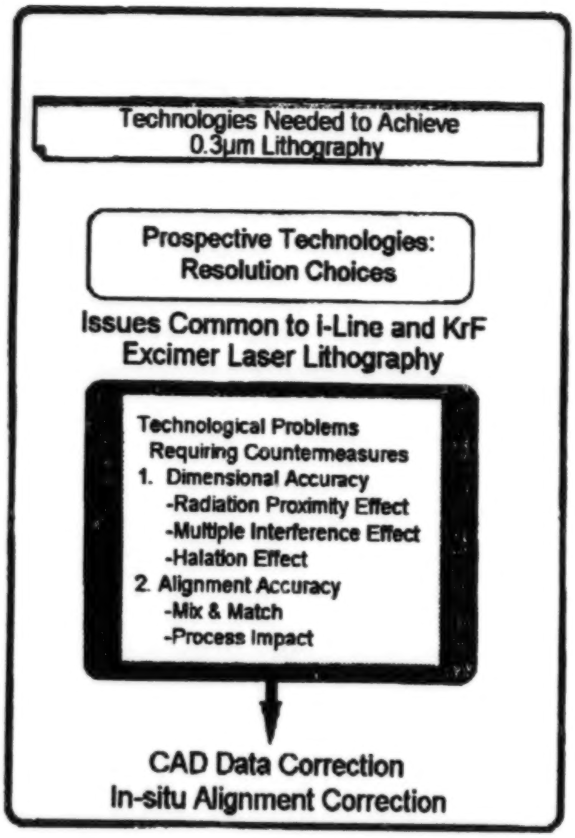
Selecting 0.3μm Lithography

Selection

Lithography Selections (i-line/KrF)
Ultra-Resolution Lithography Selections (Offaxis Illumination/Phase Shifting)
Total Cost Conversion (Existing Equipment/Between Generation Use)

Items

Resolution
Dimensional Accuracy
Alignment Accuracy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-Radiation Proximity Effect
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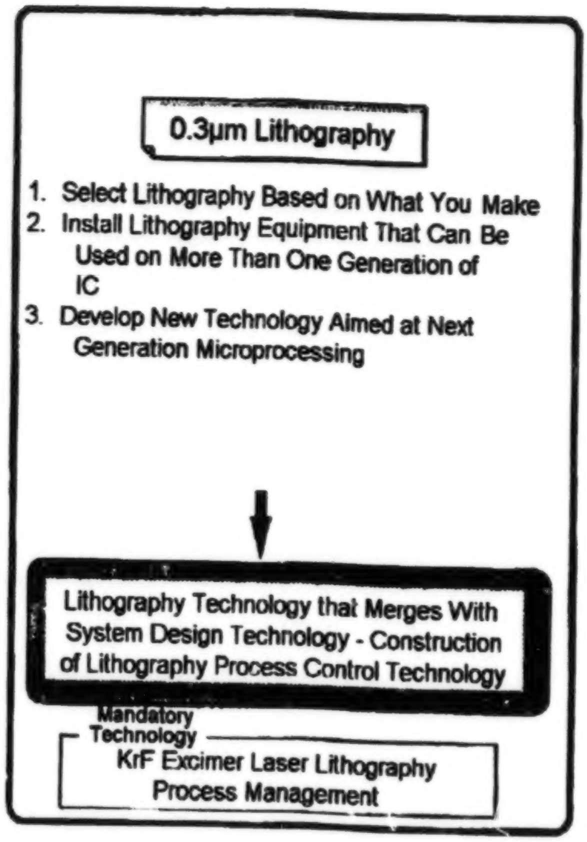
-Halation Effect
2. Alignment Accuracy
-Mix & Match
-Process Impact
CAD Data Correction
In-situ Alignment Correction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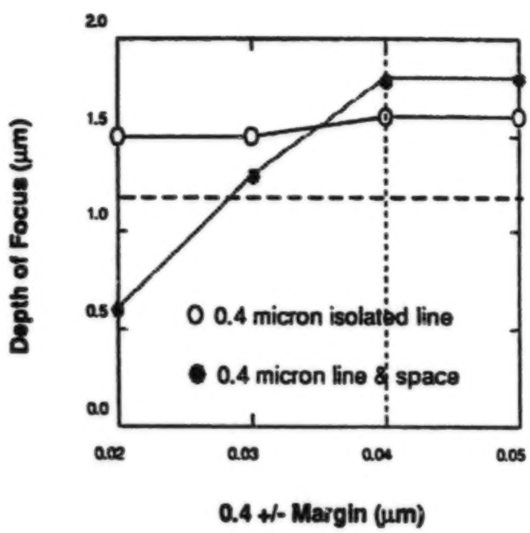
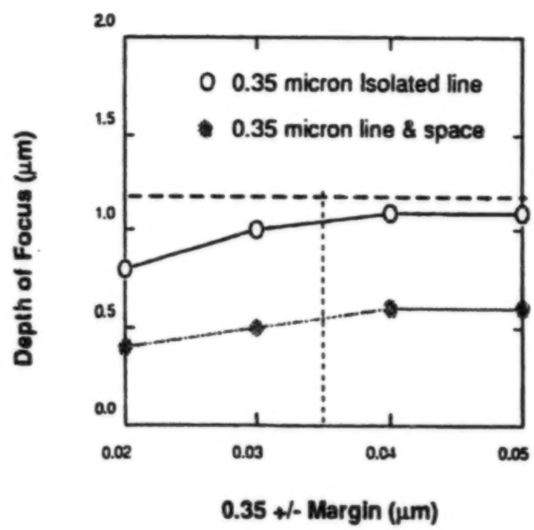
i-Line Lithography Performance

Ramdam Logic Pattern

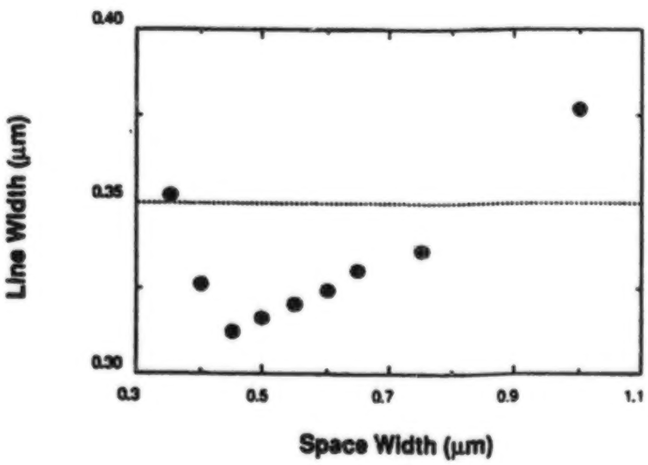


0.4 μm Rule (Margin - DOF)



0.35 μm Rule (Margin - DOF)

Proximity Effect for 0.35 μm line



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